Health and Technical Analysis of Options for Reducing Lead Emissions From Motor Vehicles in Bangladesh

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EXECUTIVE SUMMARY

Recent studies indicate that airborne lead (Pb) levels in Dhaka are among the highest in the world. Further, a blood test sample of Dhaka residents conducted by the Health Economics Unit (HEU) indicates that average blood lead levels in the city are extremely high. The significance of these findings for Bangladesh is enormous, since the presence of lead in the body is believed to create a host of health-related problems in both children and adults. The most serious of these health effects are retardation of brain development in children, elevated blood-pressure levels in adults, and associated, multiplicative negative health effects.

The situation is not beyond policy action, however. In fact, recent international studies show that for most cities, both airborne lead levels and blood lead levels decline significantly once lead is removed from motor gasoline (petrol), since lead from motor vehicles running on leaded gasoline can account for as much as 90% of lead in the environment. Because Bangladesh uses gasoline that historically has contained very high concentrations of lead, vehicular lead emissions are a principal source of lead in the air and in the populations of major urban centres of the country. Fortunately, this source of contamination can be effectively controlled, if not completely eliminated, by policy actions already undertaken by the Government of Bangladesh (GOB), policy actions which should be sustained, reinforced, and expanded.

This report presents the results from a comprehensive study of the current situation of lead emission in Bangladesh and the lead contribution from motor vehicles. It provides information on lead concentrations in gasoline, in the air, and in the blood of Dhaka residents, including the results from a blood lead testing undertaken by the HEU especially for this study. The report also provides a technical as well as cost/benefit analysis from the perspective of health economics, of issues and options for removing lead from gasoline, and presents estimates for the refinery costs of switching to unleaded fuels as well as estimates of many of the health and related benefits of switching. Finally, the report provides policy recommendations for near-term actions to reduce lead emissions and identifies future research needs in order to reduce the long-term health threat posed by lead emission.

Current Lead Situation in Bangladesh

HEU study results suggest that there is at present a lead crisis in Bangladesh. As Table ES-1 below summarises, the average lead level in blood samples collected from 39 Dhaka residents between July and October, 1997. The reported average is approximately 50 micrograms per deciliter (μg/dL)[1], roughly five times higher than the "level of concern" established by Centers for Disease Control in the United States. In fact, detrimental health impacts from lead in children have been detected at concentrations as low as 5 μg/dL. The average lead level in residents of cities around the world that have removed lead from gasoline is below 5 μg/dL. Worse still, since these samples were collected during the wet season, when air lead levels are most likely to be relatively low, the measured blood lead concentrations in the HEU sample are likely to be an under-estimation of the year-round average.

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[1] Although this is a small sample, it is statistically very significant: there is a 95% chance that the actual average blood lead level of the relevant population (Dhaka residents who work or live in downtown areas) is within +/- 9 μg/dL of this estimate if the sample is deemed as sufficiently random. Even if it is seen as a non-random sample, its results are entirely consistent with findings from other studies, and it serves as a compelling reason for further investigation of this issue.

Table ES-1. Results of Blood Lead Testing in Dhaka, July-October, 1997

Statistic	Result
Sample Size	39
Sampling Locations	Motijeel, Farmgate, Dhaka U. Area, Baridhara
Typical occupations of those sampled	Businessmen, office workers, indoor and outdoor laborers, drivers of buses, autorickshaws and rickshaws
Mean blood lead level (µg/dL)	50.9
Minimum level (µg/dL)	13.6
Maximum level (µg/dL)	132.0

These blood lead levels are very high and are a cause for serious concern. No study reviewed by the authors of blood lead levels in other countries has shown such high average levels of lead. The results of three recent air quality studies are shown in Table ES-2. These studies collected air samples at different points around Dhaka city. The first two, which collected lead below 10 micrograms in size, show that during the dry season air-borne lead levels at the tested locations are close to or exceed 1 microgram per cubic meter (µg/m^3). The third study collected lead above 10 µg in size. Taken together, these studies indicate that the total dry-season concentration of airborne lead in the sampled areas is over 1µg/m^3. Such levels are higher than those found in most other cities of the world, even though most of these cities still using leaded gasoline.

Table ES-2. Recent Estimates of Lead in Dhaka Air

Lead Particle Size Range (µm)	Air Lead Levels by Seasonal Rain-Fall Level (µg)			Source
	High Rainfall	Medium Rainfall	Low Rainfall	
0-10	0.268	0.492	0.907	Khaliquzzaman (1995)
0-10			0.999	Ahmed (1996)
>10			0.138	DOE (1997)

For notes on these estimates, see Chapter 4, Table 4.5

While Bangladeshis are likely to be exposed to other important sources of lead besides vehicular emissions, this study has not explored them. However, the high air lead levels in Dhaka indicate that vehicular emissions are clearly a very major source of lead exposure for the country's urban populations.

Costs and Benefits of Lead Reduction

The use of lead in gasoline, and its emission to the atmosphere, causes a variety of negative health impacts having very real costs to the population. However, many of these costs are difficult to quantify, as are the benefits from reducing or eliminating this lead from gasoline. The benefits of using lead, and the costs of eliminating lead from gasoline, are easier (though not simple) to quantify, and therefore society often pays more attention to them, neglecting lead's negative impacts. This study estimates that the costs associated with lead use to be very high indeed.

The basic categories of cost and benefit associated with lead use in gasoline are shown in Table E-3. There are two types of benefits and a variety of costs. From the point of view of health, the use of lead in gasoline entails serious, and for children, irreversible damaging health impacts. There is no health benefit associated with the use of lead in gasoline.

Table ES-3. Categories of Impacts from Lead Use in Gasoline

Category	Benefits of Lead Use	Costs of Lead Use
Health Impacts	(No benefits)	Wide variety of potential health impacts, including: • Retarded juvenile brain development • Detrimental cardiovascular impacts • Damage to liver and kidneys • Extensive Neurological damage
Fuel Use Impacts	• Inexpensive octane enhancement	• Accelerated wear to spark plugs and exhaust systems
Vehicle Impacts	• Protection for valve seats in older engines	• Fouling of exygen sensors on new vehicles

Health Costs as a Result of Use of Lead in Gasoline

The impacts of lead emissions on health have been the subject of hundreds of studies around the world over the past 30 years. A wide variety of health-related problems have been linked with lead in general, and gasoline has been shown to be a major source of lead exposure to humans. A summary of health-related effects is provided in Chapter 2 and the reader is referred to a companion MOHEW/HEU study on lead health impacts (Cutajar, 1997) for more detailed information.

Negative the health impacts of lead begin at blood lead levels as low as 5 µg/dL. At 10 µg/dL IQ scores (a measure of cognitive ability) in children begin to drop. At levels above 25 µg/dL, impacts on pregnancy and childbirth become pronounced, including low birthweight. At a level of about 50 µg/dL, more severe impacts of lead exposure begin to be manifest, including damage to internal organs such as liver and kidneys, impaired blood functioning, and damage to the neurological system. Above 100 µg/dL (several people measured in this range in the blood tests conducted for this study), acute symptoms can occur, including impaired mental function, delirium, convulsions, and death.

Quantifying health benefits in monetary terms is very difficult. Monetizing the effect of lower lead content in the body, and linking this to the switch to unleaded fuel, has been attempted in very few studies, and is associated with much uncertainty. Therefore, for this study it was decided to focus on conducting a detailed quantification of one health benefit of switching to unleaded fuel, rather than provide a general and simplified analysis. The benefit measure chosen is the expected increase in lifetime earnings for children due to increases in their cognitive capabilities (as measured by IQ scores) when their blood lead content is reduced. This benefit is both important and easily quantified. However, it accounted for only 1/3 of the total health related benefits as estimated by a recent comprehensive US study on the health benefits of lead reduction. As a result, the health benefits addressed in this HEU study considerably under-estimate the total health benefits from reducing lead emission.

In spite of this gross under-estimation, the health benefit alone estimated in this study is nearly 10 times greater than the total cost to society of eliminating lead in gasoline. This is because:

a) each µg/dL reduction in lead has been found to significantly increase mental capabilities as measured by IQ,
b) increases in IQ are highly correlated, and have a well established relationship, with increases in

income, and

c) there are likely to be a large number of severely lead-affected children living in Dhaka.

For reasons discussed in Chapter 7, the methodology of this HEU study focuses on the number of six-year olds impacted each year. Each year between 75,000 and 150,000 six-year olds living in Dhaka are estimated to be severely affected by airborne lead, and therefore suffer a reduction in their expected lifetime earnings. From a health economics perspective, the elimination of lead in gasoline is estimated to provide an annual benefit in (time-discounted) expected lifetime earnings of about $400 to $650 for each of these children.

Non-Health Costs and Benefits of Use of Lead in Gasoline

With respect to non-health costs and benefits, this study provides monetary estimates of the net benefits of eliminating lead and switching to unleaded fuel. The monetary estimates are based on a comparison of a system using completely leaded fuel v. one using completely unleaded fuel[2]. Most of the vehicle-related benefits of switching are also quantified. Only the benefit of being able to add catalytic converters and reduce emissions of other pollutants (a health benefit) is neglected, due to the enormous complexity involved in quantifying the health benefits from reductions in these other pollutants.

The primary benefit of lead is its use as a fairly inexpensive octane enhancer. Modern spark-ignition engines require gasoline with fairly high octane levels in order to function properly, and lead helps gasoline meet this requirement. Lead also provides a lubricative effect that protects some parts in older engines. However, the vast majority of engines on the road in 1997 in Bangladesh do not require this protection. It is useful primarily for engines built before 1980, and is only needed in vehicles that operate frequently at high speed, e.g. >100 km/hr. Two-stroke engines (used by baby taxis, tempos, and most motorcycles), regardless of age, do not at all require the protection of octane enhancement.

In fact, the use of lead has several negative impacts on vehicles and their engines. These include reducing vehicle fuel efficiency (i.e. increasing fuel consumption per kilometer), increasing the rate of wear on spark plugs and exhaust systems, and fouling oxygen sensors (which contributes to lower efficiency as well as poorer performance). In addition, motor oil becomes degraded more quickly by leaded fuel than unleaded fuel, resulting in more frequently required oil changes (or greater engine wear if more frequent changes are not made).

A secondary vehicle impact of lead is that as long as there is lead in gasoline, vehicles cannot be fitted with catalytic converters, since the fitting of catalytic converters would provide dramatic reductions in emissions of other pollutants, namely carbon monoxide (CO), hydrocarbons (HC), and oxides of nitrogen (NOx), with many associated health benefits. The main point is this: once lead is removed from fuel, vehicles can begin to be imported with catalytic converters (which should cost about the same as current imports), and reductions in emission of these other pollutants can begin.[3]

The estimated costs and benefits of eliminating lead in gasoline are shown in Table ES-4. Two cases are presented in order to reflect a range of uncertainty regarding both costs and benefits. Higher cost/lower benefit assumptions are paired in the "low benefit" case, and lower cost/higher benefit assumptions in the "high benefit" case. As shown in the table, the vehicle-related benefits alone are estimated to be virtually equal to the entire costs of switching to unleaded fuel. Without even considering health benefits, the net benefit of switching to unleaded gasoline ranges from -0.19 to 1.72 cents per liter of fuel consumed. A likely seenario might fall somewhere in the middle, around 0.75 cents per liter savings.

[2] Since lead has already been partially eliminated from gasoline in Bangladesh, some of these benefits are already being realized.

[3] It should be noted that there is a widespread misconception among many policy makers and others around the world that vehicles must have a catalytic converter in order to operate on unleaded fuel, which is untrue. Virtually any gasoline vehicle can operate on unleaded fuel with no troubles.

Most of these benefits accrue to the drivers of vehicles, since the vehicle benefits represent lower costs of owning and operating a vehicle. Most of the refinery costs are likely to be passed onto the price of fuel. Further, some benefits also accrue to passengers of buses and taxis, in the form of lower fares passed through by vehicle operators who themselves experience savings.

Table ES-4. Summary of Costs and Benefits of Switching to Unleaded Gasoline
(all units in 1997 U.S. cents per liter, except where noted. Costs are in parentheses)

Category	Low Benefit Case	High Benefit Case
1. COSTS PER LITER		
Refining costs	(1.89)	(0.88)
Vehicle-related costs	(0.01)	(0.00)
Total costs per liter	(1.90)	(0.88)
2. BENEFITS PER LITER		
Vehicle-related benefits	1.70	2.59
Lifetime earnings increase for children	16.30	52.30
Other health benefit categories	not estimated	
Non-lead air quality benefits	not estimated	
Total benefits per Liter	18.00	54.89
3. TOTALS		
Net benefits (costs), cents per liter		
Excluding health benefits	(0.19)	1.72
Including health benefits	16.11	54.02
Fuel Use per year, 1995-96 (mil. L)	189.0	189.0
Estimated Fuel Use Per year, 2000 @ 10% growth	304.4	304.4
Total Net Benefits (Costs), mil US $		
Net Benefits in 1997	30.4	102.2
Projected Net Benefits in 2000	30.2	104.0

Taking into account all the costs and benefits estimated in this study, an annual net benefit of anywhere from 30 to 100 million US dollars is estimated from the elimination of vehicular-based lead in Bangladesh. This estimate is conservative, since it excludes most of the categories of direct health benefits from eliminating lead, as well as all of the indirect health benefits that would accrue from the use of catalytic converters and their reduction in the emissions of other pollutants.

<u>Policy Issues and Options for Switching to Unleaded Fuel</u>

The Eastern Refinery in Chittagong, Bangladesh's only oil refinery, has over the past year dramatically lowered the lead content of the two grades of gasoline it produces (Table ES-5). It has been able to do this by blending in high octane unleaded gasolines that are being imported in increasing quantities to meet a rapidly increasing demand for gasoline within the country. In the past year alone, gasoline sales within Bangladesh have increased by an astounding 70%, outstripping the refinery's gasoline production capacity by a wide margin. As a result of blending this high octane unleaded product to the gasoline produced at the refinery, the need to use lead as an octane enhancing additive has decreased, and the average lead content in the regular grade of gasoline (80 octane "motor spirit", or MS-80) has fallen nearly to zero, i.e. this fuel is now virtually unleaded. The lead content of the higher grade gasoline ("high octane blending compound", or HOBC-96) has fallen by half, but at 0.40 g/L is still quite high by world standards.

Table ES-5. Average Lead Content of Motor Fuels in Bangladesh by Date
(all units in grams per liter)

Date	Regular Gasoline (MS-80)	Premium Gasoline (HOBC-96)	Weighted Avg. (for both grades)
1995-1996	0.37	0.80	0.47
February 1997	0.27	0.80	0.44
April 1997	0.08	0.80	0.14
May 1997	0.02	0.40	0.11

Source: ERL, 1997

The lead content of gasoline sold in the country will continue to decline as long as the Eastern Refinery Ltd. continues to import unleaded, rather than leaded, gasoline for blending, and as long as the percentage of total gasoline supply provided by imported blends continues to increase, which it will likely do for the next two to three years.

However, Eastern Refinery Ltd. has recently begun an effort to upgrade the refinery and has issued a tender to build a new distillation column with almost twice the capacity of the current one. If the entire refinery is upgraded to significantly increase production capacity over the next 2 to 3 years, as planned, this will be a major opportunity to ensure that unleaded fuels become a permanent fixture in the country. On the other hand, if appropriate steps are not taken to ensure that this path is followed, the refinery could return to producing leaded fuels, since it will be able to meet (for a few years) the country's gasoline demand without using large quantities of imported and largely unleaded blends.

There is no reason why the Government of Bangladesh, and the Eastern Refinery Limited, can not continue the process they have started and eliminate lead from gasoline. In fact this could be accomplished using a variety of different approaches, including several that would allow a very rapid change-over to unleaded, without waiting for an upgraded refinery to be constructed.

There are two primary issues which should be considered in developing a specific plan to eliminate lead in gasoline:

- An approach should be chosen that avoids a complex and potentially expensive transition to unleaded fuel. Such a transition is not likely to be necessary, and many countries that have taken many years to phase-in unleaded fuels now regret using this approach.

- An unleaded fuel formulation should be chosen that does not create significant new health hazards in replacing the hazard of lead. The principal concern is avoiding a high content of aromatic compounds in motor fuel.

There are a number of possible substitutes for lead that can serve as octane enhancers in gasoline. These include various reformulations of gasolines, such as aromatization and isomerization, that change the structure of the hydrocarbon compounds in gasoline, additives that improve octane in a manner similar to lead, and gasoline "extenders" that add energy value to gasoline and actually displace gasoline to a small degree while also increasing octane, such as methyl and ethyl ethers (MTBE, ETBE) and alcohols. The family of methyl and ethyl ethers and alcohols also has the advantage of "oxygenating" gasoline, reducing vehicular carbon monoxide emissions.

The relative merits of these different additives are affected by their costs as well as their health impacts. Most alternatives to lead have some health issues of their own. By far the most important is the increase in aromatic compounds caused by increased reforming of fuel. Aromatics, which are unsaturated hydrocarbons, are suspected to be carcinogens. Although vehicular emissions of aromatics in most countries are believed to account for only a small fraction of human exposure, in the case of Bangladesh the contribution could be higher due to the very high emissions of hydrocarbons by two-stroke engine vehicles

in this country. While it will always be necessary to do some reforming of naphtha in the process of producing gasoline, a worthwhile goal is to restrict the aromatic content of reformed fuel to less than 25-30% of total volume, and restrict the benzene content (the most volatile aromatic) content to less than 3%. In the US the benzene limit is now close to 1%. The high octane leaded fuel currently used in Bangladesh significantly exceeds these levels.

Bangladesh could complete its phase-out of leaded fuel very quickly by a combination of three actions:

1. Shifting to the use of higher octane (96 or higher) imported unleaded gasoline blends from the 92(RON) octane unleaded currently imported.
2. Adding other fuel additives or extenders (such as MTBE) to raise the octane of HOBC fuel while lowering both lead and possibly the aromatic content of the fuel.
3. Reducing the final octane level of HOBC fuel from 96 down to perhaps 92 or 93, since few vehicles in the country require such a high octane level. The highest octane unleaded fuel available in India is currently 87 (RON) octane. By reducing the RON level of HOBC fuel, the job of octane enhancement becomes much easier.

If and when the refinery is upgraded, it will become possible to produce unleaded gasoline without a heavy reliance on imported product blends (although of course crude oil is almost entirely imported). By constructing an isomerization unit, the Eastern Refinery can increase the octane of the gasolines it produces with few side effects, subject to the size and type of isomerization unit, and the severity at which the new reformer is operated.

Finally, one interesting option that has not been explored in this study, but deserves attention, is the use of ethanol or ETBE derived from domestic biomass as an octane enhancer. This would help keep gasoline aromatic content down, reduce vehicular emissions of CO, and provide a domestic source of octane enhancing blend that would help reduce oil imports. Ethyl alcohols and ethers can be produced from crop wastes, and if appropriate techniques are used this approach can even provide a very low greenhouse-gas fuel. As they also require the construction of a conversion plant and distribution infrastructure, and it could be an expensive option.

The key ingredients of a programme to permanently eliminate high atmospheric lead level due to vehicle emission in Bangladesh are well within reach for policy makers. In effect, they need only continue present practices of importing and blending unleaded fuels while ensuring that new refining capacity in Bangladesh will produce only unleaded fuel. If this is done, the health benefits for children and other vulnerable populations in the urban centres of the country will be substantial.

CHAPTER 1. INTRODUCTION

Several recent studies indicate that air lead levels in Dhaka are among the highest in the world. The presence of lead in air causes numerous health-related problems in both children and adults, including low birthweight in babies, retardation of the mental and physical development of children, raising blood-pressure levels in adults, and a host of serious detrimental health effects.

Since Bangladesh uses leaded gasoline (petrol) motor fuel, gasoline vehicles are a primary source of airborne lead. A recent study at Princeton University (Fanelli, 1997) has found that in most localities that have removed lead from gasoline, a dramatic reduction in the average blood lead content of their populations has followed. Many countries are now phasing lead out of motor fuels and some have completed this process. Bangladesh has not formally begun this process, but the Eastern Refinery has recently begun reducing gasoline lead content through importing and blending of unleaded fuel, and the government is interested in considering options for fully phasing out lead. The Health Economics Unit of the Ministry of Health and Family Welfare, initiated this study to assess the magnitude of health and related costs to urban populations of Bangladesh as a result of high airborne lead levels, and to identify and recommend cost-effective solutions.

1.1 Purpose and Scope of the Study

This report presents the following:

- a summary of the negative health effects of lead and recent estimates of lead emissions, air lead levels, and blood lead levels in Dhaka,
- the results of blood lead testing from a sample of Dhaka residents,
- a description of technical issues and an analysis of policy options for eliminating lead from motor gasoline in Bangladesh, and
- monetary estimates of the costs and many of the benefits associated with a complete switch to unleaded fuel.

The scope of the analysis is thus quite broad, since it includes both scientific and medical aspects (including blood testing) as well as technical, economic and policy analysis of lead reduction options. The report is intended for policy makers and provides information to assist them in deciding whether to undertake a gasoline lead elimination program, as well as how best to design such a program.

1.2 Need for this Study

This study is needed to establish the extent of the problem posed by lead emissions in Bangladesh, and to provide guidance on methods for solving the problem. It is tempting to assume outright that lead should be eliminated from motor vehicles, since this is the conclusion that has been reached by virtually all developed countries, as well as many developing countries. However, given that Bangladesh is one of the poorest countries in the world, the costs of removing lead from its motor fuels must be weighed carefully against the health and other benefits of doing so, to ensure that such a policy decision would be beneficial to the society.

Lead is a serious poison. As discussed in Section 3 below, there is strong evidence that exposure to even small amounts of lead can cause a variety of health problems, both acute and chronic. Perhaps the most alarming (but certainly not the only) problem is the impact of lead on the brain development of children. In Dhaka, children spending considerable time near major roadways are very likely exposed to levels of lead sufficient to impair brain development and reduce their learning ability. Other children and adults may also be affected in significant ways.

In addition to lead's health impacts, presence of lead in motor fuels creates three other types of problems. First, it accelerates wear on certain engine parts and significantly increases the cost of maintaining a vehicle. Second, it increases the average fuel consumption of vehicles relative to their operation on unleaded fuel. Third, it seriously hinders the viability of other emissions reductions options. Emissions of NOx, HC, and CO, the main precursors to smog and ozone, and serious air pollutants in their own right, cannot be directly controlled at the vehicle tailpipe for vehicles running on leaded fuel. This is because the primary mechanism for controlling these pollutants, the "three-way" catalytic converter, is applicable only to vehicles using unleaded fuel.. Thus removal of lead from gasoline is a critical step to tackling several other important air pollution problems associated with motor vehicles.

In order to understand the extent of these problems in Bangladesh, and how the problems are likely to change in the future, a technical analysis of vehicle lead emissions is needed. In order to know exactly how much of this lead is ingested by the inhabitants of the urban areas of the country, blood lead testing is needed. Together these investigations provide a picture of the size and seriousness of the problem. By coupling this information with an analysis of the steps necessary to reduce or remove lead from fuel, and the costs of these measures, a picture of the costs and benefits of lead reduction can be assembled. With this information, policy makers can then make informed decision, taking into account both the benefits and costs of lead reduction.

1.3 General Methodology

This study requires several analytic methods which are described in the appropriate sections below. For all aspects, the analysis has involved a review of the primary and secondary literature and discussions with individuals who have relevant knowledge and information to share. Written and verbal information have been obtained in the following areas:

- Lead effects on human health;
- Lead emissions and lead levels around the world and in Bangladesh;
- Lead testing methods used and results obtained in other countries;
- Vehicle travel, fuel use, and emissions in Bangladesh;
- Refinery practices and lead use in fuels in Bangladesh;
- Vehicle fuel requirements and effects of lead removal on vehicles in Bangladesh;
- Lead reduction programs and experiences in other countries
- The costs of alternative lead reduction schemes in Bangladesh.

The authors made two excursions in their efforts to obtain information and data for this study. They traveled to the Eastern Refinery in Chittagong for one full day of interviews, and they traveled to Calcutta, Delhi, and Dehra Dun in India for five days of interviews (see Appendix A for a list of interviews). During these interviews a tremendous amount of verbal and written information was obtained that is relevant to this analysis, and was used throughout the report.

Two primary analyses were conducted. The first is the collection and testing of blood samples taken from residents of Dhaka for the presence of lead. The results were used to test the hypothesis that the high levels of airborne lead measured in Dhaka are being absorbed by the residents of the city and are present at dangerous levels in their blood. The tests were conducted during the wet season when air lead levels are lower than average, so a finding of significant blood lead levels at such a time represents an under-estimation of the magnitude of the problem. A detailed discussion of the methodology used for this testing work is contained in Chapter 5.

A second primary piece of analysis for this report is the analysis of technical issues and options for eliminating lead in gasoline. Estimates of the costs of lead reduction and quantification of some benefits are provided in this report. Recommendations are made regarding the advantages and disadvantages of different approaches. Key steps involved in this analysis include:

- Determining the fuel requirements of the current and likely future vehicle fleet in Bangladesh.

- Determining the composition of unleaded fuel that meets these vehicle requirements in the most cost effective and safest manner.

- Developing alternative approaches to modifying the Eastern Refinery, or taking other steps, in order to produce the required fuel.

- Developing efficient approaches and policies for switching from the current fuel system to a new unleaded fuel system.

- Estimating the costs of the necessary measures, including costs associated with the switching from leaded to unleaded fuel. These are then compared to those benefits that can be estimated, to determine the net costs or benefits of lead removal from gasoline.

1.4 Limitations of the Study

There are a number of issues that this report does not address or resolve completely. A detailed refinery cost analysis would require development of a comprehensive refining model at the Eastern Refinery. Constructing such a model is beyond the scope of this study. However, the refining cost estimates provided herein are believed to be reasonable approximations of the costs that would be derived from such models, and more importantly, of the actual costs of lead removal. These cost estimates are based in part on data provided by the refinery, and have been reviewed by refinery officials.

The blood lead testing conducted for this study has involved a small sample (about 40 individuals), and has been conducted during only one part of the year (the part least likely to indicate a serious lead problem). A more complete testing study, with a much larger sample in more areas and covering a full year would be required to fully characterize the extent to which the population in this country suffers from acute or chronic lead exposure and how lead exposure varies by demographic, socioeconomic and geographic group.

Finally, there are some issues that simply are not sufficiently well understood to allow a definitive assessment to be made. After nearly 30 years of study, the effects of lead on the human body are still not understood well enough to be beyond debate. However, the consistently strong correlations found between lead levels and certain health problems have been sufficiently persuasive to move many countries into action. In any case, as shown below, the benefits from removing lead from motor fuels appear to be dramatic even with relatively conservative assumptions regarding health benefits.

1.5 Organization of this Report

Chapter 2 provides an overview of lead impacts on human health.

Chapter 3 discusses issues related to lead use in motor vehicles, and options for replacing lead.

Chapter 4 provides an overview of vehicles and fuels used in Bangladesh, including a discussion of their technologies and emissions characteristics. It also presents estimates of the quantities of vehicular lead emitted in the country and in Dhaka.

Chapter 5 describes the methodology and results of the blood lead testing carried out as part of this study.

Chapter 6 provides a discussion of issues relevant to removing lead from gasoline and replacing lead with other octane enhancers. This includes a description of the refinery operations in Chittagong and issues related to both the fuel distribution system and vehicle requirements when developing a lead phase-down scheme. Various policy options for switching to unleaded fuel are considered.

Chapter 7 provides estimates of some of the key categories of costs and benefits (including health benefits) of switching to unleaded gasoline.

Chapter 8 presents a summary and conclusions of the research, and recommends policy action and additional research needs for the future.

CHAPTER 2. LEAD EXPOSURE PATHWAYS AND IMPACTS ON HUMAN HEALTH

2.1 Introduction

This chapter provides a summary of the pathways by which individuals are exposed to lead and the health impacts of this exposure. A more complete discussion of the latter is provided in Cutajar (1997), a companion report also published by the Health Economics Unit.

Lead is a heavy metal. It is not part of human constitution, and it does not have any known biological value in humans. Its presence in the body produces a number of negative physiological effects. A blood lead level of about 10 µg/dL (micrograms per deciliter) is regarded as the initial "level of concern" for children because lead toxicity begins to have clear manifestations at that level (US CDC, 1991), although some studies have found effects at lower levels and there is no agreement on a "threshold" level below which blood lead is not a concern. The mean blood lead (Blood lead) level of a cross-section of people in Dhaka city taken seventeen years ago was found to be 56 µg/dL (Khan *et al.*, 1980 - see Chapter 4), and the testing work for this study has found even higher levels (Chapter 5). Thus, the situation clearly has worsened over the years and demands urgent attention.

2.2 Forms of Lead

The rate of absorption of lead, and therefore its toxicity in practical terms, depends on the chemical form of the lead compound. It also depends on the exposed person's age, sex, smoking and drinking habits (Annest and Mahaffey, 1984), and is correlated with socioeconomic status (Roberts *et al.*, 1985). Dermal (skin) exposure to metallic lead does not pose any great danger to human health as long as the exposed areas are properly rinsed with plenty of water. Lead is mainly absorbed as inorganic and organic lead compounds.

Organolead compounds are generally more toxic than inorganic lead compounds (Wong, 1978). Of the two most commonly used organolead additives, tetraethyllead (TEL) and tetramethyllead (TML), the first is somewhat more toxic than the second (Gherardi *et al.*, 1962; Magistreti *et al.*, 1963; Springman *et al.*, 1963). TEL and TML are also known by their organic class name, tetraalkyllead. Tetraalkyllead compounds break down in internal combustion engines to produce trialkyl lead salts. It is believed that these trialkyllead salts are responsible for the toxicity of organolead additives (Cremer, 1959; Stevens *et al.*, 1960).

Although lead is added to gasoline as organolead compounds, automobile exhausts mainly contain inorganic lead compounds and a little unburned organolead additives. Amongst the inorganic compounds detected in roadside air are usually lead sulfate and halides or double salts with ammonium halides, *e.g.*, bromolead chloride:bis(ammonium chloride), bromolead chloride:ammonium bromide:ammonium chloride, and similar inorganic complexes (De , 1994; Biggins and Harrison, 1979). Once lead compounds escape into the environment, they only undergo transformation from one lead compound to another. Elemental lead cannot degrade in the environment.

2.3 Lead Exposure Pathways

2.3.1 Lead in Atmosphere, on Land, and In Water

Although most automobile emissions of lead are to the atmosphere, much of this lead is soon removed from atmosphere by wet and dry deposition processes. Wet deposition occurs by the rinsing effects of rain water, and dry deposition takes place by gravitational settling or Brownian deposition on surfaces such as land, water and plants. As a consequence of these processes, street dust and roadside soil become enriched with lead which eventually gets further washed into roadside ponds, lakes or rivers. Therefore, individuals living in areas of high automobile lead emissions may ingest a significant amount of this lead by drinking water or through contact with soil. Wet deposition is by far the most important process by which atmospheric lead is removed. It accounts for 40-70% of deposition (Nielsen, 1984). In Dhaka during the monsoon season, the concentration of lead in atmosphere has been measured at 0.268 µg/m^3 (mean value of samples for fine plus coarse particles) compared to a mean value in the dry season of 0.907 µg/m^3 (Khaliquzzaman *et al.* 1995).

Lead deposition depends on the particle size. Heavier particles (>2 µm in diameter) are usually deposited near the source, whereas lighter particles are carried farther (Nriagu, 1979; IPCS, 1989). About 20-60% of emitted lead is found within 25 meters of the source of emission (ATSDR, 1993). In rural Bangladesh farther afield (50 km) from the busy roads of Dhaka, in the interior areas of Savar (6 km from the extensively used highway at a height of 7 m above ground), the concentration of air-borne-fine lead particles is low (0.035 μg m^{-3}) in the low rainfall period compared to that of Dhaka (0.463 μg/m^3 at 50 m away from a busy road in Dhaka city at a similar height) during the same period. The bromine to lead ratio was found to be 0.3 in Savar indicating that a part of this low lead comes from sources other than automobile exhausts (Khaliquzzaman *et al.* 1995 and 1996).

Because most air-borne lead is carried as fine particulates, it can travel some distance. In a house near the roadside, even in the absence of any indoor source of lead such as lead-based paint the inside air can have as much lead as 60% of that in the nearby outside air (Davies et al., 1987). Thus a person in a high-lead area probably will not escape exposure even if he/she stays indoors most of the time. High indoor lead levels are especially likely in cities like Dhaka where, due to hot weather conditions, many people keep their doors and windows open much of the time.

2.3.2 Absorption of Lead from Air

The absorption of lead from air takes place *via* inhalation and depends on the magnitude of the deposition and how it takes place. The extent of deposition is between 30-50% depending on the particle size and the rate of ventilation. Small particles of less than 0.5 μm in diameter which are usually borne by ambient air and will be deeply imbedded in lungs are efficiently absorbed (up to 90%). Larger particles which are deposited in the upper air-way, are either dissolved in the lungs or are swallowed subsequent to particle clearance and absorbed in the gastrointestinal tract. The absorption of inorganic lead through unbroken skin is considered negligible.

Table 2.1 presents the relationship between air lead levels and typical daily absorption of lead by adults and children. Inhalation of ambient air-borne lead is of course just one route of intake. Total lead-intake will also depend on exposure to other routes such as ingestion of food, water, smoking tobacco, drinking alcoholic beverages, contact with dust & soil, use of lead-based cosmetics and traditional medicines, and other pathways. However, as discussed in Chapter 3, below, airborne lead has proven to be the principal source of lead in take in most cities where thorough testing has been conducted.

Table 2.1. Estimates of Absorption of Lead by Adults and Children from Air

Mean air lead concentration (μg/m^3)	Amount of lead absorbed daily (μg/day)	
	Adults	Children
0.3	2.4	0.6
0.5	4.0	1.0
1.0	8.0	2.0
2.0	16.0	4.0

source: adapted from WHO (1987)

There is considerable evidence to suggest that increased intake of dietary calcium decreases the absorption and retention of lead in infants, young children and adults (Mahaffey, 1985). The converse is also true. For example, in low-income families, there is often an association between low dietary intake of calcium, iron deficiency, and elevated blood lead levels (Yip and Dallman, 1984; Mahaffey, 1985). This is due to the chemical similarity between lead and calcium ions. In Bangladesh where the consumption of both iron and calcium is inadequate, the lead absorption and retention may be unduly facilitated.

2.3.3 Distribution of Absorbed Lead in the Body

Once lead is absorbed, it moves quickly to blood and other soft tissues such as liver and kidneys. This is followed by a slower redistribution into bone, teeth and hair. Only a small amount of absorbed lead circulates in the blood at one time. In adults about 94% of the body burden of lead is located in the bones, while in children, 73% of the burden is situated in the bones (Barry, 1975, 1981). Under a steady state, 96% of blood lead is in the erythrocytes (Manton and Cook, 1984).

The half-life of lead in blood is about 28-36 days (Rabinowitz *et al.*, 1975). The half-life of lead in soft tissue is approximately 40 days, and that in bone is the longest, nearly 27 years. Once lead is settled into the various compartments of bone, it seems to remain there for a long time (Rabinowitz & Kopple, 1976; Marcus, 1985). Bone acts as a repository as well as an endogenous source of lead (Silbergeld, 1991; Manton, 1985; Schultz, 1987).

2.3.4 Indicators of the Body Burden of Lead

The degree of exposure and subsequent level of absorption of lead in the body may be ascertained by determining the lead content of several body tissues, e.g. blood, bones, teeth and hair.

Blood lead: Soon after an exposure, the blood-lead level increases. The concentration of lead in blood thus indicates recent exposures. Lead does not stay in blood over a prolonged period. As mentioned above the half-life of lead in blood is only 28-36 days, and accordingly lead gradually moves into other tissues. Lead in blood originates predominantly from the exposure to the environmental lead (exogenous source). A less obvious source of blood-lead is endogenous. Lead re-enters the blood stream from other tissues where it was originally transferred from blood for storage. This endogenous transfer occurs during tissue mobilization.

Bone lead: Lead is transferred to bone from about the time of fetal development up to the age of about 60 years , and its level measures the long term exposures. Lead is mobilized from bone during pregnancy and lactation (Silbergeld, 1991) and osteoporosis (Silbergeld et al., 1988).

Dentin Lead: This indicator is more relevant to the assessment of the extent of exposure of a child. Lead is accumulated in children's teeth during the stages of the development of teeth. Tooth-lead thus reflects accumulation from pre-natal exposures to the time of shedding of the teeth (Needleman *et al.*, 1972; Fergusson *et al.*, 1989; Hansen *et al.*, 1989).

Hair lead: Hair lead-level has been employed as bio-indicator of lead exposure mainly for children, but less successfully than other indicators mentioned above (Whilhelm et al., 1989; Marlowe and Errera, 1982).

2.4 Impacts of Lead on Human Health

The effects of lead on human health may be considered under the following headings: the biochemical effects, the effects on haematopoietic system, nervous system, renal system, cardiovascular system, effects on liver, reproduction and bone, and gastrointestinal effects. An excellent review published by WHO (1995) gives a great deal of details on the research done in this area. These impacts are also reviewed in a companion HEU study (Cutajar 1997).

2.4.1 Haem Synthesis

Haem is the oxygen carrying component of haemoglobin, produced during the development of red blood cells. Lead affects the biosynthesis of haem by interfering with the normal functioning of three enzymes which play crucial roles in the synthesis. These enzymes are 5-aminolaevulinate dehydratase (ALA-D), coproporphyrinogen oxidase (COPRO-O), and ferrochelatase (FERRO-C). As a result of this interference metabolic intermediates such as ALA and COPRO, and zinc-bound protoporphyrin, which are precursors of haem, accumulate and are finally excreted. In children the concentration of erythrocyte protoporphyrin increases substantially when their blood-lead level is 15-25 µg/dL. For adult men such increases are detected at a blood lead level of 25-30 µg/dL, and in adult women at 20-30 µg/dL. The results are more complex when the subjects suffer from iron deficiency (Piomelli *et al.*, 1982; Roels *et al.* 1976; Marcus and Schwartz, 1987).

The overall effect of the interference with the haem synthesis is that haemoglobin along with some respiratory pigments *e.g.*, cytochromes requiring haem as precursor, are not synthesized, which then interferes with the transport of oxygen throughout the body.

2.4.2 Vitamin D Deficiency

The formation of the vitamin D metabolite, 1,25-dihydroxy-vitamin D, is inhibited by high level of lead in blood. For example, Rosen *et al.* (1980) observed a decrease of vitamin D in serum at blood lead level of 33-35 µg/dL in children, with the effect becoming dramatic at 65 µg/dL.

2.4.3 Haematopietic System (Anaemia)

One of the consequences of lead poisoning is the development of anaemia, and as such anaemia has been recognized as a symptom of lead toxicity. Anaemia results when haemoglobin that gives erythrocyte their red color is in short supply or when erythrocytes, the carrier of haemoglobin, are more rapidly destroyed than are formed. According to a US EPA (1986) the threshold blood lead-level when anaemia becomes noticeable is 50 µg/dL. Schwartz *et al.* (1990), reported that in children, the onset of anaemia is observed at a blood lead-level of 40 µg/dL.

2.4.4 Nervous System

Lead affects three components of the nervous system: the central nervous system (CNS), peripheral nervous system (PNS), and autonomic nervous system (ANS).

Central nervous system (CNS): Severe lead poisoning gives rise to abdominal pain, constipation and paralysis, a condition collectively known as lead 'encephalopathy'. At blood lead levels greater than 80 µg/dL, intense encephalopathy and or coma may occur. Lilis *et al.* (1977) found that of 158 secondary lead smelter workers examined, 64% complained of pronounced CNS symptoms. They all had high blood lead level, averaging about 70 µg/dL.

Peripheral nervous system: Peripheral neuropathy is caused by chronic, high level exposure to lead. One of the symptoms of this illness is the feeling of weakness of the upper and lower limbs. At a lower level of exposure, decreased nerve conduction velocity (NCV) is taken as a measure of peripheral nervous dysfunction. Several recent reports indicated that at blood lead levels above 30 µg/dL, NCV is substantially reduced (Seppalainen *et al.*, 1983), although this is disputed (Davis and Svendsgaard, 1990).

Autonomic nervous system: Some dysfunction of the autonomic nervous system has been observed by at least two groups of researchers (Teruya *et al.*, 1991; Murata and Araki, 1991). The second study found impacts amongst male workers with an lead levels averaging 36 µg/dL (range 5-76 µg/dL). This study reveals that lead poisoning effects may be perceptible even at such a low level of exposure as 5 µg/dL.

2.4.5 Neurotoxicity in Children

Compared to adults, children are more susceptible to the effects of lead poisoning. In children, the symptoms of lead toxicity such as encephalopathy, anaemia, low haemoglobin count, raised erythrocyte proporphyrin, slowed nerve conduction velocity, and impaired neuro-behavioural function, begin to show up at much lower levels of blood lead than in adults. Children can also suffer potentially permanent reductions in the brain development, and secondary symptoms of lead poisoning include poor academic achievement and somewhat diminished awareness and intellectual performance (US EPA 1986, 1990).

2.4.6 Kidney and Liver Damage

It is known that acute exposure to lead causes kidney damage. Weeden *et al.* in 1979 observed lead induced nephropathy among certain workers with blood lead in the range of 40-80 µg/dL Buchet *et al.* (1980) found evidence of renal toxicity above a blood lead level of 62 µg/dL. Long term exposure to lead at an elevated level can also lead to impaired liver function. The liver becomes less able to metabolize drugs (IPICS, 1995).

2.4.7 Reproductive System

The reproductive processes of both men and women are reported to be adversely affected by lead poisoning. In the case of females, the risk of spontaneous abortion has been found to increase, along with a reduction in infant birth weight, at a blood lead level of below 30 µg/dL (Nordstrom *et al.*, 1978). In men sperm morphology and function is altered at blood lead levels between 40-50 µg/dL.

2.4.8 Cardiovascular System

Hypertension (high blood pressure) is a primary cause of heart attacks and strokes in adults, especially males. Extensive research has been done to determine whether or not there exists a causal relationship between the body load of lead and hypertension in humans. What has been established so far is that there exists a weak correlation between them. However, there is evidence from animal studies that lead has an adverse effect on blood pressure (IPICS, 1995).

2.4.9 Effects on Bone

Because of the chemical similarity between calcium and lead ions, lead collects in bone, but as mentioned above, during tissue movements, bone-lead is transferred to some target organs and blood. Thus, bone-lead acts as an internal reservoir of lead, and may impact indirectly on health. A more direct adverse-effect of lead on bone is its contribution to the development of osteoporosis (IPICS, 1995).

2.4.10 Gastrointestinal Effects

Acute lead poisoning gives rise to colic. The symptoms of colic include abdominal pain, cramps, nausea, vomiting, constipation, anorexia, weight loss and diminished appetite. Colic is observed when severe lead poisoning occurs (blood lead levels of 100-200 µg/dL) (Baker *et al.*, 1979; Pollock and Ibels, 1986), although some researchers have found that colic may be observed at a much lower level of exposure, 40 µg/dL (Schneitzer *et al.*, 1990).

2.5 Conclusion

The effects of long-term low-level exposure to lead are not yet fully understood. However, there is no doubt that exposure to moderate and high levels causes several serious health problems in humans. These problems become magnified by low dietary intake of calcium and low iron status. In Bangladesh, where nutritional deficiency is common, high level of airborne lead and high blood-lead in its people is a cause for serious concern.

CHAPTER 3. LEAD USE IN MOTOR VEHICLES

3.1 Benefits of Using Lead in Motor Vehicles

Lead is used as an additive to motor fuels primarily to raise fuel octane and thereby enhance the performance of spark-ignition engines. It is also needed in some older vehicles as a lubricant that protects engine piston valve seats. A more detailed description of lead's role as an octane enhancer in gasoline engines and related technical issues is provided in Appendix B.

1.1.1 Gasoline Engine Operation and Lead as an Octane Enhancer

Vehicles with spark ignition engines generally use gasoline (petrol) fuel, while compression ignition vehicles use diesel (distillate) fuel. In Bangladesh as in most countries, vehicles with spark-ignition engines running on gasoline include almost all cars, motor cycles, and auto-rickshaws (baby taxis, mishuks, and tempos), as well as most small trucks, vans, and jeep-type vehicles, and some buses (see Chapter 4). Diesel engine vehicles do not use lead additives in order to deliver satisfactory performance.

Under some circumstances there is a tendency of gasoline to pre-ignite in the piston (knocking) and it varies considerably with the chemistry of the gasoline. The "octane rating" of a fuel provides an index of its resistance to pre-ignition. In general, straight-chain hydrocarbons have low octane value, and branched-chain hydrocarbons and aromatic hydrocarbons have relatively high octane values. Thus refinery gasoline conversion processes aim at producing gasolines with highly branched as well as aromatic hydrocarbons. There are three different methods for measuring the octane of gasoline (discussed in Appendix B), the most common being the "research octane number" (RON).

Lead has proven to be a technologically efficient and cost-effective, additive for the purpose of increasing the octane rating of gasoline. Lead is added to gasoline in the form of organic-lead compounds, most commonly tetra-ethyl-lead (TEL) and tetra-methyl-lead (TML)[4]. Depending on the initial octane rating of the gasoline, and the desired final octane rating of the gasoline, different amounts of lead may be added to the fuel. The addition of less than 0.1% by volume of TEL or TML to gasoline is found to increase its RON octane rating by 10-15 points. If enough TEL or TML is added, even an initially low-octane (or "low-grade") gasoline performs smoothly in high compression engines without knocking. Leaded fuel around the world varies from about 0.05 to over 1.0 gram per liter of lead content (Octel, 1995).

1.1.2 Lead as a Lubricant for Valve Seats

In addition to serving as an octane enhancer, lead is known to provide a lubricative benefit for certain engine parts, especially the "valve seats" where the fuel air mixture enters and exits the piston. Older valve seats were made of a steel that was prone to corrosion and recession under some circumstances without the protective coating provided by lead compounds in the fuel. However, the importance of lead in this role has been debated and a significant amount of research on this issue was conducted in the 1970's and early 1980's. Concern over the impact of removing lead from gasoline on valve seat wear in certain older cars has prompted some countries to avoid allowing older cars to run on unleaded fuel, and as a result has caused long phase-in times for the introduction of unleaded fuel.

The U.S. EPA (1985), in their cost benefit analysis of fuel lead reduction, reviewed over 20 studies of both controlled experiments and road-test studies conducted in the late 1960's and 1970's on the impacts of unleaded fuel on valve seats.

The controlled experiments as reported by EPA found that valve recession results from abrasion and

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[4] Commercially there are three other alkyl leads available as well. These are dimethyldiethyllead (DMDEL), methyltriethyllead (MTEL), and trimethylethyllead (TMEL) (De, 1994).

adhesion on the valve seat when engines operate for continuous periods under high speeds and engine loads (and thus under high temperatures and compression levels). Most laboratory tests were conducted using speeds and engine loads much greater than those under normal driving conditions (e.g. with speeds up to 160 km/hr). Most of these test studies found that the rate of valve-seat wear accelerates rapidly at speeds above 70 miles per hour (about 110 km/hr). EPA quoted one study as saying:

> The data shown here also indicate that the average driver, who seldom exceeds 70 mph, should not experience significant engine deterioration while using lead-free gasoline. The salesman, however, who drives 15,000 turnpike miles per year at 80 mph, may well expect valve train problems.[5]

This is cooroborated by virtually all the studies reviewed, finding the impacts of unleaded fuel on valve seats to be negligible at speeds below 100 km/h.

The EPA study found that tests of most vehicles built after 1970 showed especially few problems. This is because in 1971 all manufacturers producing vehicles for the U.S. market began producing cylinders with hardened valve seats, in anticipation of the U.S. lead phase-down program. Most major international manufacturers changed over their production of all vehicles to supply them with hardened valve seats during the early 1970s.

It can therefore be said that although at one time the issue of valve seat wear was an important concern for cars running on unleaded fuel, it has become a virtual non-issue in 1997 for the vast majority of the cars on the road. In Bangladesh, there is the additional factor that very few cars ever have the opportunity to exceed 110 kph, and most cars in Bangladesh built before 1980 are now in such condition that they are hardly capable of reaching such speeds.

3.2 Vehicle Problems Associated with the Use of Lead

Several problems associated with the use of lead additives in gasoline have been identified. These primarily involve accelerated corrosion to certain engine parts. In addition, a reduction in fuel consumption per kilometer has been found in vehicles that have switched from leaded to unleaded fuel. Thus, the use of lead additives in gasoline reduces fuel efficiency.

3.2.1 Lead as a Corrosive to Engines

Several studies conducted between 1969 and 1981 have found that, although lead provides some benefit as a valve-seat lubricant, it also accelerates corrosion of some engine parts. The primary beneficial impacts of reducing fuel lead content have been found with respect to spark plugs, exhaust systems, and oil quality (and the required frequency of oil changes).[6]
The U.S. EPA, in its 1985 cost-benefit analysis performed as part of its rulemaking on lead levels in leaded gasoline estimated that the net benefits to engines, engine oils, and exhaust systems from reducing lead levels from 1.1 to 0.1 grams per gallon (0.3 to 0.024 grams per liter) "will yield benefits of about $17 per year for a vehicle driven 10,000 miles". This amounts to about $200 in (time-discounted, 1985 dollars) savings over the 15 year life of a vehicle.

3.2.2 Fuel Efficiency Impacts

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[5] EPA (1985), p. VII-29. Quoting Giles and Updike, (1971), TRW corp., p. 2369.

[6] An Australian study (Mowle, 1981) found very significant reduction in the need for changes of spark plug, engine oil, oil filters, and mufflers as aresult of switching to unleaded fuel. This resulted in time discounted savings over the life time of the vehicle of between US$300-600. A Canadian study conducted in 1980 (Cantwell) found results similar to the Australian study.

Switching from leaded to unleaded fuel creates four separate impacts on fuel consumption per kilometer of travel. Three of these reduce and one increases fuel use. The fuel-use increasing impact results from a decline in refinery efficiency when producing unleaded fuel. The Australian study (Mowle 1981) found that refineries consume about 1% more energy when producing unleaded gasoline than leaded gasoline. This is due primarily to the energy required to for increased reforming and isomerization.

The three fuel-use reducing impacts are related to a) increased energy density of unleaded fuel, b) reduced fouling of oxygen sensors in newer vehicles (caused by lead), and c) reduced fouling of spark plugs from lead. The greatest increase in fuel efficiency was found by the Australian study (Mowle, 1981) which estimated that vehicles running on unleaded fuel (after several years) were 5% to 10% more fuel efficient than those running on leaded fuel. They did not separate out the relative impacts of the three effects in deriving this estimate.

Taking into account all the impacts, an estimate of 2% to 4% improvement from switching to unleaded fuel seems reasonable.

3.3 Alternatives to Lead Use for Fuel Octane Enhancement

The problems associated with lead use have spawned a host of alternative methods for increasing the octane of gasoline. These approaches are not without drawbacks, however. They are generally more expensive than lead and some produce emissions of other harmful compounds.

3.3.1 Reformulated Gasolines

The concept of reformulating gasoline relates to changing the molecular structure of the hydrocarbons it contains, which is one of the approaches for octane enhancement and reducing emissions of air pollutants. There are three primary processes that can be used to increase fuel octane: alkylation, isomerization and aromatization (see Appendix B for details).

Alkylation is a process in which high octane fluids with branch-chained carbon skeletons are obtained by the alkylation of straight-chained hydrocarbons of low octane value. Catalysts are typically used in this process.

Isomerization produces branched-chain hydrocarbons with enhanced octane ratings by employing catalysts to carry out the reactions under mild conditions.

Aromatization was initially an important component of lead free fuels in most countries undertaking such programs in the 1980s. However, increasing evidence that aromatic compounds are carcinogenic gave rise to serious concerns about their use and most unleaded fuel in developed countries now has a far lower percentage of aromatic compounds. The U.S., which used to have fuels with up to 5% benzene (perhaps the most dangerous aromatic compound, since its high volatility makes it more likely to enter the atmosphere), now allows only 0.5% benzene content (US EPA, 1991).

While it is clearly important to limit vehicular emissions of aromatic compounds, it should be noted that gasoline emissions of aromatics are generally considered to be much less of a health threat than emissions of lead. This is true for two reasons:

1) Compared to lead, aromatic compounds are relatively short-lived in the atmosphere (hours or days); in contrast, lead is elemental and therefore is a persistent compound which can remain in the human environment for many years.

2) Other sources of aromatics, especially of benzene, generally far outweigh vehicles as sources of exposure for most people, even if there is high benzene content in gasoline. In the US, Wallace (1989) found that only 20% of benzene exposure could be attributed to traffic and industrial emissions. Smokers' benzene exposure rates have been found to exceed non-smokers exposure rates by 10 times.

It has been estimated that in the U.S. in the 1970s, approximately 50 "excess deaths" per year were attributable to exposure to vehicular benzene emissions (primarily due to leukemia), while exposures to vehicular lead emissions resulted in 4,000 to 5,000 annual deaths (Lovei, 1997).

Emission of aromatic compounds, on the other hand, can be controlled through the use of catalytic converters, which convert most hydrocarbons into water and carbon dioxide before they enter the atmosphere. Given that virtually none of two-wheel and three-wheel two stroke vehicles in Bangladesh has been fitted with catalytic converter, the tailpipe emissions of aromatic compounds are quite high.[7]

In addition to tailpipe emissions, a considerable amount of aromatic compounds are released as evaporative emissions. This can occur at all times, even when a vehicle is not running. For automobiles with catalytic converters, evaporative emissions are now believed to account for the majority of benzene emissions from vehicles (Thomas, 1995). Furthermore, it is now increasingly clear that the greatest exposure to vehicular aromatic emissions, in developed countries at least, occurs not from ambient emissions but from situations where emissions are heavily concentrated in a small space, such as in a closed garage after a car has been parked for several hours or during refueling when the refueler may breath heavy doses of evaporative emissions.

In balancing all of these considerations, it seems that although concerns regarding aromatic emissions should not prevent a lead reduction program from going forward, minimizing the aromatic content of unleaded fuel should be a very high priority in choosing the method for producing unleaded fuel. The use of isomerization (to reduce reliance on reforming) is one way to reduce aromatic content. There are several other methods, generally involving the use of other blending compounds.

3.3.2 Use of Other Blending Compounds to Increase Octane

In addition to gasoline reforming and isomerization, there are a number of different additives that can be used to increase the octane of gasoline. These include fuel "extenders" that add energy content to the fuel as well as change the chemical properties of the fuel. The most commonly used extenders are the oxygenates: alcohols such as methanol and ethanol and ethers such as methyl-tertiary-butyl-ether (MTBE) and its ethyl equivalent (ETBE). Methyl-cyclopentedienyl manganese tricarbonyl ("MMT") is also commonly used to enhance octane. Oxygenates are gaining in popularity around the world in part because they provide other environmental benefits besides lead displacement. Their high oxygen content allows fuel to burn more completely and reduces emissions of carbon monoxide. These additives are generally more expensive than refinery options such as reforming, especially if the refinery has spare capacity in an existing reformer.

Ethyl-based oxygenates (ETBE and ethanol) offer another potential benefit: they can be produced from biomass feedstock, offering an opportunity to displace imported oil with domestically produced fuel[8]. Bangladesh has an enormous amount of biomass, and much of the biomass waste produced in the country is used in relatively low-value applications such as household cooking. If households could sell some of this waste to an alcohol or ETBE biomass conversion plant, they could increase their earnings considerably.

In addition to offering a domestic source of high-octane gasoline blends, biomass-based oxygenates can provide significant greenhouse gas reductions, depending on the conversion processes used to obtain the liquid fuel from the feedstock. Research in the US and other countries on using woody biomass and advanced conversion processes has indicated that ETBE or ethanol could be produced in such a way as to produce 90% less greenhouse gas emissions than the gasoline it displaces (Delucchi, 1997).

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[7] Auto-rickshaws and motorcycles in India using two-stroke engines have been estimated to emit up to 40% of their fuel as unburned hydrocarbons (Pundir et al, 1994). Virtually the same vehicles are used in Bangladesh.

[8] Methyl-based oxygenates (MTBE and methanol) can also be produced from biomass feedstock, but the ethyl compounds are generally preferred for economic and performance reasons (US DOE, 1997).

CHAPTER 4. VEHICLES, FUEL USE, AND LEAD EMISSIONS IN BANGLADESH

4.1 Vehicle Types and Fuel Use in Bangladesh

Table 4.1 lists the major vehicle categories and the number of registered vehicles in 1995 in Bangladesh for each type.

Table 4.1. Types and Estimated Numbers of Motor Vehicles in Bangladesh

Vehicle	Engine Type	Primary Fuel Type	Number (1995)
Automobile	SI 4-stroke	Gasoline	66,000
Jeep/minivan/microbus	SI 4-stroke	Gasoline	30,000
Small bus	CI	Diesel	14,000
Large bus	CI	Diesel	11,000
Truck	CI	Diesel	36,000
Three-wheel vehicle (Auto Rickshaw)			60,000
Tempo	SI 4-stroke	Gasoline lub oil	
Baby taxi	SI 4-stroke	Gasoline lub oil	
Mishuk	SI 4-stroke	Gasoline	
Motorcycle / scooter	SI / 4-stroke	Gasoline	184,000
Total Number of Gasoline Motor Vehicles			340,000[9]
Total Number of Gasoline + Diesel Vehicles			400,000

Source: Bangladesh Road Transport Authority, 1997

From the table it can be seen that, according to BRTA, there are perhaps 340,000 gasoline vehicles in the country, of which over half are motorcycles[10]. Cars and autorickshaws account for about 18% and 17% of the total vehicle stock respectively. Trucks and buses each account for less than 10% of the vehicle stock.

The growth in the stock of each type of vehicle during the 1990's is presented in Table 4.2. The fastest growing type of vehicle in Bangladesh during this time has been the auto-rickshaw, which grew by 19% per year over the past two years. Automobiles, jeeps and microbuses (minivans), and trucks also grew at 6% or more per year. If recent rates of growth continue, the stock of vehicles will double to over 800,000 vehicles by 2005, and autorickshaws will double their share of the total (from 17% to 34%).

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[9] A small number of cars, jeeps and minivans, probably run on diesel, while there may be a significant number of small and medium-sized trucks that run on gasoline. Estimates of the percentages of each are provided in Table 4.3.

[10] The BRTA data for number of motorcycles is significantly higher than some other estimates, such as Gallagher (1993). If it is accurate, it seems likely that the vast majority of motorcycles are used outside Dhaka.

Table 4.2 Growth in Vehicle Stock, 1990 - 96, and Forecast for 2005

Vehicle Type	Vehicle Stock in Selected Years			Annual Growth Rates		Estimated Number of Vehicles in 2005 at Recent Growth Rates
	1990	1994	1996	1990-96	1994-96	
Motor Car	46.577	56.233	65.760	4.8%	5.9%	110.318
Jeep Microbus	19.576	27.022	30.105	8.4%	7.4%	57.413
Bus	12.321	13.168	13.627	1.7%	1.7%	15.850
Minibus	8.296	9.683	10.890	3.9%	4.6%	16.378
Truck	25.471	29.742	36.095	4.0%	6.0%	60.890
Autorickshaw	21.054	38.152	59.691	16.0%	19.0%	284,951
Motor Cycle	133.534	169.389	183,814	6.1%	5.5%	296,865
Total	266.829	343.389	399.982	6.5%	7.0%	842,666

Source: growth rates from BRTA 1997; forecast by authors

By estimating the annual kilometerage of each vehicle type and the average fuel consumption per kilometer, an estimate can be obtained of the fuel consumption of each type of vehicle. Estimates for 1996 are presented in Table 4.3.

Table 4.3. Estimated Travel and Gasoline Consumption by Vehicle Type, 1996

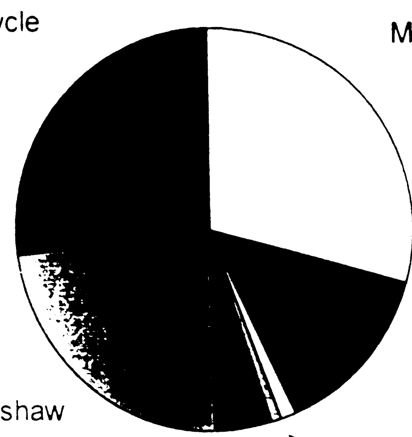
Vehicle Type	Numbers of Vehicles, 1996	Avg. Kilometers per Vehicle per Year	Typical Veh. Efficiency (liters per 100 km)	Fuel Fuel Consump. (mil. liters per year)	Pct of Fuel Use that is Gasoline	Gasoline Consumption (Mil liters per year)
Motor Car	65.760	14.000	9	83	98%	81
Jeep Microbus	30.105	14.000	12	51	75%	38
Bus	13.627	40.000	25	136	2%	3
Minibus	10.890	40.000	20	87	2%	2
Truck	36.095	50.000	25	451	2%	12
Auto Rickshaw	59.691	18.000	6	64	100%	64
Motor Cycle	183.814	10.000	4	74	100%	74
Total	399.982			946		274

Sources: vehicle numbers, BRTA (1997); travel data, Gallagher (1993), fuel efficiency and percentage gasoline fuel use, various sources and authors' estimates[11]

The fuel consumption by vehicle type is also presented in pie-chart format in Figure 4.1. As shown in these charts, cars are the number one consumer of gasoline in the country, followed closely by motorcycles (and scooters) and autorickshaws. Although trucks and buses are the leading consumers of motor fuel, they mostly consume diesel, so they only account for a small fraction of gasoline consumption and lead emissions.

[11] The data in the table are based on the assumption that the average annual travel per vehicle is unchanged from 1993, when Gallagher (1993) made those estimates. The numbers in the table must be considered as preliminary and need further verification; however they result in an estimate of gasoline consumption that is within 10% of the estimate of total gasoline supply for 1996 provided by the Eastern Refinery (about 250 million liters - see table 6.3).

Figure 4.1 Consumption of Gasoline by Vehicle Type



Source: authors' estimates; see Table 4.3

4.2 Fuel Use and Lead Emissions

Since most lead in gasoline that enters the engine eventually is emitted from the exhaust pipe, vehicle emissions of lead are closely proportional to the product of vehicle fuel consumption and fuel lead content. If all vehicles used the same type of fuel then the only difference in lead emissions across vehicle types would be due to rates of fuel consumption. However, as in most countries, not all vehicles run on gasoline in Bangladesh (most trucks and large busses use diesel - see Table 4.3), and there are two grades of gasoline with a significantly different average lead content. These are the 80 octane "motor spirit" (MS-80) and the 96 octane "octane" or, more technically, "high octane blending compound" (HOBC-96). An estimate of the quantity of lead emitted to the atmosphere by fuel grade in 1995-96 is shown in Table 4.4. During 1997, the lead concentration of both fuels has been lowered significantly by the Eastern Refinery, to nearly zero for MS-80 and about 0.4 for HOBC-96. This means that vehicles running on MS-80 now emit almost no lead to the atmosphere. The implication of this development is discussed further in Chapters 6 and 7.

Table 4.4. Gasoline Lead Content and Lead Emissions in Bangladesh, 1995-96

Fuel Type	Average lead content per liter of fuel (gm liter)	Liters of fuel consumed (million liters)	Lead emitted to the atmosphere (mil gm)
MS-80	0.365	142.0	41.5
HOBC-96	0.8	47.2	30.2
Total (avg.)	0.474	189.2	71.7

source: see Table 6.1. Assumes that 80% of lead in fuel is emitted to the atmosphere.

Different vehicles use different amounts of the two grades of gasoline, since drivers can choose either grade and many blend the two by refueling partly with each. Cars and trucks running on gasoline often use at least some high octane fuel, whereas 2-wheel and 3-wheel vehicles generally use only the lower grade of fuel. It can therefore be said that cars and gasoline-powered trucks are currently the primary contributors of vehicular lead emissions in the country, while two and three-wheel vehicles running on MS-80 currently contribute very little lead (although they contribute a great deal of aromatic compound emission which is carcinogenic).

As shown in Table 4.4, 71.7 million grams of lead, or about 200 million micrograms per day, are emitted throughout the country. If half of this were emitted in Dhaka in a 25 square km area up to 10 meters in height, this would represent about 0.4 $\mu g/m^3$ of emissions per day throughout this area. This represents pure lead, and measured air lead levels includes non-lead particle matter that the lead attaches itself to. Further, actual air concentrations will likely vary considerably within this area, as the vast majority of emissions are along the major traffic corridors and in crowded downtown areas, and, thus, the actual air concentration of lead would be much higher in these areas. The estimate therefore suggests that vehicle emissions of lead are very high, and are probably sufficient to account for high tested air lead levels.

4.3 Ambient Lead Levels in Dhaka

In Bangladesh the levels of lead (and all other pollutants) in the atmosphere have not been monitored on a regular basis until very recently. However, three recent studies provide estimates of lead concentrations in Dhaka's air. Each of these studies has involved taking air samples at regular intervals over several months, at specific locations in Dhaka, and testing the samples for the presence of a variety of compounds, including metals and other air pollutants. Lead results from these studies for specific sites are presented in Table 4.5.

Taken together, the three studies have found ambient lead levels in the tested locations to be very high by international standards. Results in the table below are shown in terms of air lead concentrations during both the wet and dry seasons.

Table 4.5. Recent Measurements of Lead in Dhaka Air

Particle Size (µm)	Location	Rain-Fall Levels			Source
		High	Medium	Low	
2 - 10	Ramna (commercial)	0.108	0.239	0.444	Khaliquzzaman (1995)[12]
< 2		0.160	0.253	0.463	
0-10 total		0.268	0.492	0.907	
0-10	Farmgate (commercial)			0.999	Ahmed (1996)[13]
>10	Farmgate commercial)			0.183	DOE (1997)[14]

For the Khaliquzzaman study, the testing work was conducted as part of an international project of the International Atomic Energy Agency, Vienna. Under this program, measurements are made under similar analytical conditions in many different countries of the world where such facilities exist. Using the same

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[12] The samples were collected using a Gent stacked filter sampler at a height of 7 m and at 50 m from the road during Aug-'93 - Dec '94, in front of the Atomic Energy Center, Dhaka. Particulates 2-10 mm were collected by a coarse filter and particulates < 2 mm by a fine filter using nucleopore filter of 47 mm diameter. The analysis was carried out using the PIXE method.

[13] The samples were collected during Mar-April, 1996, using a High Volume Air Sampler (APM 415 Environtech, India) with gaseous sampling attachment (APM 411) set 1 m from the roadside and at a height of 1 m above ground. Particulates 2-10 mm were collected by coarse filter and particulates <2 mm by fine filter. The samples were analysed by Shimadzu Atomic Absorption Spectrometer (AAS).

[14] The samples were collected during Nov '96- - Feb '97 using a High Volume Sampler (Envirotech APM 410/451) with gaseous sampling attachment (APM 411), and Whatman glass fibre filter (10 mpore-size). The analyses were carried out using an AAS. The result shown is an average of three measurements. DOE stands for the Department of Environment of the Government of Bangladesh.

system, only three or four other locations (out of the nearly 100 cities involved) have found air lead concentrations to be as high as those found in Dhaka. Cities with similar lead levels (as those taken here during the dry season) include Kathmandu, Calcutta, and Mexico City, all cities that are well known to have serious air quality problems. From the table it can also be seen that the study measured a similar concentration of coarse and fine lead particles in the air, and that the level increases significantly during the dry season. The similarity in concentration of coarse and fine particle lead is somewhat surprising since studies carried out in other countries generally indicate that 70% to 80% of airborne lead is in the form of fine particles (Burton and Suggs, 1982).

The second study (Ahmed, 1996) was conducted in a similar manner, except samples were collected at 10 locations around the city, and collection was done only during the dry season (March-April 1996). The readings were generally similar to the first study. The 3-day average readings ranged from about 0.4 to 1.1, with a maximum reading of 1.4 $\mu g/m^3$.

The third study, conducted by the Bangladesh Department of Environment, used a filter of 10 mm pore-size (Reazuddin, 1997). Since almost all air-borne lead is bound to fine particles less than 1 mm in diameter, using a filter of this size was able to capture only the few coarse particles in the air (US EPA, 1986a; WHO 1987). However, if the DOE value is added to those of either of the other studies, the total dry-season lead content of the air near the road-side may be calculated, and appears to be in the range of 1.1 to 1.2 $\mu g/m^3$. These measurements are above the WHO recommended maximum level of 0.5 $\mu g/m^3$.

Dispersion modeling work done on lead further suggests that in heavily traveled areas in Dhaka, especially at major intersections, ambient lead concentration may be even higher than concentrations at the measured sites. In general, such modeling efforts have indicated that the lead concentration in air diminishes rapidly with distance from major intersections and roadways. One study on the distribution of automobile-generated lead in the air, carried out in Philadelphia (Burton and Suggs, 1982), revealed that the concentration of lead decreased very rapidly from the roadway out to 75 meters, and after that more slowly out to 175 meters.

The results of the Khaliquzzaman study also suggest that the atmospheric lead measured by his study originates almost entirely from automobiles. This is indicated by the amount of the element Bromine measured by the study. The bromine-to-lead ratio was found to be in the range of 0.25 in the fine particulate fraction collected during the dry season, a ratio that is close to the ratio of bromine-to-lead emitted by vehicles. Similar ratios have been found in other studies where the ambient lead was traced to motor vehicles as the principal source (EPA, 1986a, WHO, 1987).

4.4 Air Lead Levels and Blood Lead Levels

The intake of lead by individuals is dependent on the type of exposures they suffer, their lifestyles, and socioeconomic conditions. However, past studies have indicated that there is a strong correlation between air lead levels and blood lead levels.

The recent Princeton study (Fanelli, 1995), which reviewed a number of lead analyses from cities and countries around the world, has estimated the change in blood lead levels with change in air lead levels to be 4 (+/- 1 at a 95% confidence interval), i.e. for each 1 $\mu g / m^3$ change in air lead levels, blood lead levels increase by 3 to 5 μg per deciliter, with an intercept (average blood lead level in the absence of any air lead) of 6 μg per deciliter (+/- 3 μg at the 95% confidence interval). This implies that a person exposed to 2 $\mu g / m^3$ of air lead will experience blood lead levels between 9 and 19 μg per deciliter. However, blood tests in many cities have found significant numbers of people with blood lead levels much higher than these, suggesting perhaps that this equation understimates the results of exposure at the high end, or exposure levels that have been in excess of 2 $\mu g / m^3$. This could occur in very localized areas even if average air lead levels are below 2.

4.5 Previous Tests of Blood Lead Levels

The level of lead in blood is generally accepted as an accurate measure of the extent of recent lead exposure and risk of serious impacts from this exposure. Testing blood lead levels and correlating this information with individuals' locations of living and working activity can also be a useful method to learning how and where lead exposure occurs. The half-life of lead in blood is 4 to 5 weeks (IPCS, 1995). Lead has a much longer half-life in bones and teeth, and accumulates there, and tests of teeth are considered better than blood for providing an indication of long-term lead exposure, particularly for children since lead is collected in teeth during their formation. However, for obvious reasons blood tests are more practical to administer on a random sample of the populace.

There has been one previous study that measured the blood lead of residents in Dhaka (Khan et al, 1980). This study was conducted 17 years ago when there were fewer cars on the road than today. The study sampled blood from 93 residents. Results are shown in Table 4.6. The analysis was carried out using the external beam PIXE spectroscopy technique (at the Bangladesh Atomic Energy Center, Dhaka laboratory). The sample was chosen randomly from among Dhaka residents. No details were given regarding the socioeconomic characteristics of the sample.

Table 4.6. Lead Concentration in Human Whole Blood in Dhaka, 1980

Units	Range	Mean	Median	Recommended Maximum Level
parts per million (ppm)	0.2 - 1.0	0.53	0.55	0.15
micrograms per deciliter (μg/dL)	21 – 105	56	58	0.0

source: Khan et al. 1980. Recommended maximum level from US CDC, 1991. Note: conversion from ppm to μg /dL based on assumed density of blood of 1.05 g/ml for males and 1.04 for females.

The mean value of 56 μg/dL indicates a very high level of lead in the blood of the 93 people sampled. If the lead was absorbed from air alone, then lead pollution by autos was most likely a serious problem at that time. The levels are in fact so high as to suggest that there may be a significant source of lead besides automobile emissions. These estimates are compared to more recent estimates in the following chapter.

CHAPTER 5. BLOOD LEAD TESTING IN DHAKA: METHODOLOGY AND RESULTS

5.1 Sampling Methodology

The approach taken in this study has been to (i) sample Dhaka residents, and (ii) target specific groups considered particularly at-risk for high air lead exposure. The sampling outline is presented in Table 5.1, reflecting the target sample sizes and actual samples collected (to date).

Table 5.1. Sampling Strategy for Blood Testing Work

Type of Sample	Target Sample Size	Sample Collected
Random Sample	50	8
Selected Over-sampled Groups		
Street-beat and Traffic Policy Officers	10	1
School Children	10	1
Rickshaw Drivers	10	6
Baby-taxi Drivers and assistants	10	11
Professionals in Urban Neighborhoods (e.g. Motijeel, Farmgate)	10	12
Total Sample Size	100	39

Special care has been taken to make sure that although considerable oversampling has been conducted in terms of occupations, the samples were collected from a wide range of individuals, in terms of age, income, education, locations of home and work, and travel patterns.

In order to ensure that a wide range of individuals were sampled, and to allow statistical analysis of the correlations between lead levels and socio-economic and geographic factors to be performed, a demographic survey has been conducted in conjunction with the blood testing work, gaining key information from each person tested. The survey obtained the following information:

- Sample number, date and location of test
- age, income (range), occupation and education level of respondent
- residence and work location: distance of travel between
- mode of travel to work
- length of time working at this job
- marital status and number of dependents
- presence of illnesses
- blood pressure level (taken during interview)
- If high blood pressure, then duration and family history (if known)
- vegetarian / non-vegetarian
- smoker / non-smoker: if smoker, for how long?
- How many cigarettes do you smoke a day currently?

The smoking-related questions were added near the end of the current round of sampling, when the authors became aware that lead may be present in tobacco.

5.2 Sample Collection Approach

Collection of blood samples was conducted using a mobile blood collection unit. This is a motor vehicle equipped with a principal sampler and one of the authors (M.T. Rahman), a trained nurse, blood collection equipment, blood pressure equipment, and a facility for sample storage in the air-conditioned vehicle.

Blood was collected using disposable (sterilized), plastic syringes imported from Japan. The blood samples were stored in sealed, sterilized new glass tubes (Vacuette brand made by Greiner Labortechnik, a German company) with EDTA added (an anti-coagulant). These samples were delivered at the end of each collection effort to the laboratory where the analysis was done. Blood pressure was taken using a portable, manually operated BP instrument. Blood sample collection was carried out from July through October, 1997. A total of 39 samples were collected.

5.3 Blood Testing Methodology

The blood analysis work was conducted by the University of Dhaka, Department of Chemistry. It was supervised by Professor A.H. Khan, under subcontract to this study. Samples were stored in a refrigerator before the actual analysis, which was completed within 2 -3 days of receipt of the samples.

The method used for analyzing the samples was computer-controlled voltametric, using a thin film of mercury electrode as the analytical sensor. This method provides a minimum detection level of 5 parts per billion (ppb), which is quite sensitive and more than adequate for the measurement of lead, which in this case was present in the parts per million (ppm) range[15].

5.4 Blood Testing Results

The overall results of the blood testing of 39 samples is shown below in Table 5.2. The average blood level of those tested was over 50 μg/dL. It is disturbingly high. Every person tested had a measured lead level above 10 μg/dL and all but one had a level above 20. Perhaps most surprisingly, levels were very high regardless of whether the person tested was young or old; of high or low income; indoor or outdoor working.

Table 5.2. Summary Results of Blood Tests

Statistic	Age	Income (Taka per Month)	Blood Lead (mg/dL)
Mean	33.7	10,968	50.9
Median	32.0	4,000	46.0
Minimum	15.0	0	13.6
Maximum	70.0	100,000	132.0

note: 44 taka = $1

As shown in Table 5.3, the average blood lead level is very high in virtually all categories. While there is indeed some variation in average lead levels across categories, the sample sizes are too small to allow statistically significant correlations to be obtained. Further, few clear correlations appear from visual examination of the table. While "outdoor" laborers have among the highest lead levels and "indoor" workers among the lowest, it is clear that working primarily indoors does not make individuals immune from lead exposure: "professionals" have an average over 50 μg/dL. This may be due to the fact that most professionals tested work in Motijeel, an area with very heavy traffic. Somewhat surprisingly, baby taxi drivers and rickshaw pullers do not have especially high levels of blood lead. The one student tested lives and attends school in Baridhara, a relatively low-traffic area.

[15] It would be useful to compare the tests conducted on this equipment to tests of the same samples on other machines using atomic absorption spectroscopy (AAS) and/or PIXE. This would provide a cross-check on the results.

Table 5.3. Breakout of Blood Lead Level by Respondent Category

Occupation Category	Number of Respondents	Avg. Lead Level (mg/dL)
Driver	1	86.0
Outdoor laborers	3	79.3
Policeman	1	77.0
Professionals	12	55.8
Housewife	1	49.0
Rickshaw pullers	6	46.3
Baby-taxi drivers	11	44.6
Indoor workers	2	25.0
Student	1	13.6
Unknown	1	32.0

While it would be useful to collect additional samples, in order to increase the sample size sufficiently to conduct more detailed statistical analysis of correlates, the overriding message is already present in this 39 sample data: blood lead levels in Dhaka are very high - up to 12 times higher than the "level of concern" prescribed by the US Centers for Disease Control.

CHAPTER 6. ISSUES IN REMOVING LEAD FROM MOTOR GASOLINE

6.1 Current Eastern Refinery Gasoline Production Practice

As mentioned in Chapter 4, two grades of gasoline are sold commercially in Bangladesh. These are HOBC-96 and MS-80. Lead is added to both of these grades, although during 1997 the amount added to both fuels has declined significantly and MS-80 is now almost lead-free.

In order to produce the two grades of gasoline, two fuel streams are used at the Eastern Refinery. The process of distillation produces two grades of naphtha, known as "light gasoline" and "heavy gasoline". These two intermediate products ultimately become MS-80 and MS-96 respectively, after several additional steps of treatment. These steps serve several purposes, but are primarily for increasing the octane of the two fuels. The process used was changed significantly in March 1997 and it results in fuels with rather different characteristics than they previously had, although the octane ratings are unchanged. The methods used before and after March 1997 are discussed below.

6.1.1 Gasoline Production Prior to Spring 1997

The process for producing MS-80 from light gasoline and HOBC-96 from heavy gasoline prior to spring 1997 is shown in Table 6.1 The data are taken from the 1995-96 fiscal year (as reported by ERL) but are also representative for earlier years. In this process, the light gasoline stream has an initial naphtha with a RON rating of 62. It is first put through the Merox unit, which sweetens the fuel (modifies and removes impurities such as sulfur compounds) but does not increase the octane. The fuel is then blended with higher octane reformate (see discussion below) and other intermediate products that increase octane slightly, to 64-66 RON, and enhance fuel quality. Finally, tetra-ethyl lead is added to bring the octane rating up to 80 RON.

For heavy gasoline, the initial RON rating is quite low - 50 to 52. This naphtha is first put through a reformer, which substantially increases its octane primarily by creating aromatic compounds that have a high RON value. Fuel coming out of the reformer (known as "reformate") has a RON rating of 86 - 88. Blending components are then added to improve fuel quality (which lowers the octane rating slightly). Finally, tetra-ethyl lead is added to bring the fuel octane up to 96 RON.

6.1.2 Gasoline Production Since Spring 1997

Beginning in about March 1997, the Eastern Refinery modified the technique used to produce MS-80 and MS-96. The switch involved a significant reduction in lead, and initiated the use of imported unleaded product as a blending component. Representatives at the refinery gave three primary reasons for the switch:

- ERL was concerned about the high lead content and had recently decided, with the approval of the Bangladesh Petroleum Corporation, to lower the lead content.
- Demand for motor fuels had out-stripped refining capacity to such a large extent that imported gasolines now constituted a significant proportion of total gasoline sold. This meant that by blending of high-octane imported fuel, significant changes to the final fuel octane rating were now possible.
- The refinery found that by switching to importing unleaded 92 RON gasoline instead of lower octane leaded gasoline, and blending this with their light gasoline, the resulting octane could be brought up close to 80 RON at a cost commensurate with (or even lower than) using lead for this purpose.

Differences between this and the previous approach are most noticeable for the light gasoline stream. The majority of the imported fuel is unleaded 92 RON. When blended with the 60-62 RON Naphtha, the resulting fuel has a RON rating of nearly 80 with no lead added. A small amount of lead is added to bring the final RON up to 80. This compares to the earlier light gasoline process in which less than 20% of the light gasoline stream came from blends, and none of this blend was from imported gasoline (only the refinery's own 75 RON BKD condensate and 86- 88 RON reformat). These previous blends had served to increase the octane of the 62 RON naphtha by only 2 to 4 RON. This left a large required increase of octane to be provided by lead, that is now filled by unleaded imported gasoline.

In the heavy gasoline stream the need to bring the RON level up to 96 means that the job cannot be done only by blending 92 RON unleaded. Further, since the entire heavy gasoline stream is put through the reformer, it has a RON of 86-88 before being blended. A significant amount of unleaded 92 has now begun to be blended in the heavy stream. In April 97, this amount was 1753 metric tons, a ratio of almost 1:2 with the heavy gasoline naphtha. This is substantial (though less than in the light stream where the ratio is more than 1:1), but it increases the heavy gasoline RON by only about 1 point, from about 87 to 88. Lead is still used to bring the octane up to 96 RON. Clearly, shifting to an imported gasoline blend with higher RON would have a significant impact on the RON of the resulting refinery product, with less lead requirement.

The results of these changes in refining technique are shown in Table 6.1, which presents data on the production of MS-80 and HOBC-96 yearly, 1990-1996, and monthly since July 1996. The amount of lead (in grams per liter) used in the two fuels was fairly constant (0.3 to 0.5 for MS-80 and 0.8 for HOBC-96) until March 1997, when it dropped dramatically with the introduction of unleaded blending component. In May 1997, lead content dropped to 0.02 g/L for MS-80 and was about 0.4 g/L for HOBC-96 due to the continue rise in imported unleaded gasoline blends.

Thus, in the new process, the shift to blending a large quantity of 92 RON brings up the octane of MS-80 to the required level with only nominal use of lead. ERL representatives stated that they expect the amount of unleaded 92 octane imported to be of sufficient quantity (due to rising overall fuel demand) to soon allow 80 octane fuel to be produced without the use of any lead.

6.1.3 Impacts of the ERL's Recent Changes

The recent changes in gasoline production technique have resulted in a situation where there is now one grade of motor fuel (the lower grade, MS-80) in the market that is or will soon be virtually unleaded, while the other grade (HOBC-96) still contains a significant amount of lead (although less than it used to). This means that certain vehicles on the road - those operating only on MS-80 - will soon be operating on unleaded fuel. The reduction of lead in gasoline, especially MS-80, represents a very significant step on the part of ERL, and one that will provide immediate health benefits to the public. The average lead content in all gasoline has declined by a factor of 4 to 5 since February 97 (see last column in Table 6.1).

Table 6.1. Annual Production of Gasoline and Consumption of Lead at Eastern Refinery, Chittagong

	Gasoline Production (ERL) (metric tonnes)			Total Gasoline Supply ERL + Imported blends (k liters)			Input of Lead Compounds (metric tonnes)			Unleaded Fuel (k liters)		Avg. Gasoline Lead Content (grams / liter)		
Year	MS	HOBC	Total	MS	HOBC	Total	TEL	TML	Lead-only tot	MS	HOBC	MS	HOBC	Combined
1985-86	51,639	0	51,639	75,623	0	75,623	163.13	1.08	64.7			0.86	1.10	0.86
1986-87	51,426	10,843	62,269	75,539	14,645	90,184	155.43	70.37	89.0			0.96	1.10	0.99
1987-88	51,116	8,096	59,212	78,678	11,041	89,719	149.05	14	64.2			0.66	1.10	0.72
1988-89	62,461	11,346	73,807	89,780	15,309	105,089	89.79	25.13	45.3			0.37	0.80	0.43
1989-90	75,219	16,787	92,006	109,266	22,667	131,933	128.67	41.28	67.0			0.45	0.80	0.51
1990-91	78,914	12,182	91,096	114,812	16,396	131,208	95.26	47.03	56.1			0.37	0.80	0.43
1991-92	87,516	17,943	105,459	128,316	24,257	152,573	103.69	71.44	69.1			0.39	0.80	0.45
1992-93	106,852	21,191	128,043	156,682	28,635	185,317	162.1	63.54	89.0			0.42	0.80	0.48
1993-94	93,016	25,994	119,010	136,394	35,125	171,519	126.41	62.83	74.6			0.34	0.80	0.43
1994-95	107,448	31,582	139,030	157,556	42,676	200,232	142.34	95.49	93.8			0.38	0.80	0.47
1995-96	96,846	34,915	131,761	142,010	47,180	189,190	156.26	71.24	89.7			0.37	0.80	0.47
JUL '96	11,226	4,290	15,516	16,654	5,851	22,455	20.98	8.72	11.7			0.43	0.80	0.53
AUG'96	9,913	5,178	15,091	14,825	6,995	21,820	17.5	9.09	10.5			0.34	0.80	0.49
SEP '96	11,940	4,256	16,196	17,509	5,823	23,322	21.75	8	11.7			0.41	0.80	0.50
OCT'96	13,008	4,631	17,639	19,117	6,291	25,408	19.96	10.54	12.0			0.37	0.80	0.47
NOV'96	11,166	3,770	14,936	16,326	5,169	21,495	19.4	6.91	10.4			0.38	0.80	0.48
DEC'96	11,093	4,134	15,227	15,910	5,665	21,575	21.84	6.54	11.2			0.41	0.80	0.51
JAN'97	9,545	4,344	13,889	14,180	5,910	20,090	7.07	16.72	9.4			0.33	0.80	0.47
FEB'97	9,919	4,969	14,888	14,876	6,786	21,662	13.6	10.18	9.4			0.27	0.80	0.44
MAR'97	9,268	6,191	15,459	30,497	8,400	39,048	4.32	7.63	4.7	14,357	2397	0.04	0.40	0.12
APL'97	8,602	5,601	14,203	29,685	7,615	37,300	5.53	10.18	6.2	14,535	2,414	0.08	0.40	0.14
MAY'97	7,471	3,432	10,903	23,297	4,672	27,969	7.11	0.37	2.9	9,200	3,220	0.02	0.40	0.11
JUNE'97	14,923	4,962	19,885	39,851	6,740	46,591	13.23	1.45	5.8	15,554	2,720	N/A	N/A	N/A
1996-97	128,074	55,758	183,832	252,727	75,917	328,735	172.29	96.33	105.9	53,646	10,751	0.24	0.68	0.35
JULY'97	4,937	5,732	10,669	26,778	7,827	34,605	4.36	4.36	3.4	12,167	7,453	N/A	N/A	N/A
AUG'97	8,819	5,818	14,637	26,832	7,857	34,689	7.89	1.09	3.5	7,152	6,740	N/A	N/A	N/A
SEP'97	9,957	5,011	14,968	20,021	6,818	26,839	10.62	3.27	5.5	1,627	3,658	N/A	N/A	N/A

However, this change raises two questions. One is whether the lead is being replaced by other additives that might themselves cause health impacts; another is whether the new fuel mix will have any negative impacts on vehicles in Bangladesh.

Potential health impacts of new fuel formulations relate primarily to the aromatics, especially benzene. Aromatic compounds are suspected of being carcinogenic. Benzene is of greatest concern because it is the most volatile aromatic compound and therefore the most likely to find its way into human lungs.

There is no available information on the aromatic content of the imported unleaded fuel used for blending. However, the aromatic content of the current HOBC leaded fuel is very high. The Eastern Refinery does not receive any data on the aromatic content of fuel it blends, although it tracks the content of the gasolines it produces. It has reported aromatic content in the leaded gasoline it produces as follows:

	Benzene	Aromatic
MS-80:	0.4% - 1.5%	2% - 6%
HOBC - 96:	6% - 10%	35% - 40%

Imported unleaded blends added to MS-80 (where most blending occurs now) probably do raise the benzene and overall aromatic content of this fuel, but it is unlikely that they increase the already high levels in HOBC-96.

While concerns over aromatics probably should not stand in the way of a lead reduction initiative, it would be prudent to move toward lower aromatic content fuels in the near future, regardless of the presence or absence of catalytic converters on vehicles. As discussed in Chapter 3, a significant percentage of vehicular aromatic emissions do not pass through the tailpipe, but are evaporative and are released whether or not the vehicle is operating, and regardless of the presence of a catalytic converter (Wallace, 1989). India has mandated that gasoline have no more than 5% benzene, with this limit expected to drop to 2% by 2000. The Phase II limits in California (the strictest in the world) are set at about 1% (Pundir et al, 1994).

Methods for reducing aromatic content include building an isomerization unit at the refinery, which can produce high octane lead with low aromatic content, and adding oxygenates, such as MTBE or ETBE, for octane enhancement purposes. In the short run, the refinery can take a major step by inquiring and ensuring that imported gasoline blends are low in aromatics.

The second issue is whether the unleaded MS-80 fuel now being produced is safe for all vehicles using it. As discussed in Chapter 3, lead provides a lubricative effect and has been shown to reduce wear on valve seats in older 4-stroke spark-ignition engines (newer engines with hardened steel valve seats do not need this protection). The vehicles that are most at risk of experiencing accelerated valve seat wear are those that were made before 1980 (at least for most Japanese models, which represents the vast majority of vehicle imports in Bangladesh). Further, most of the accelerated wear is believed to occur at very high speeds (over 100 km/hr), which few vehicles in Bangladesh achieve for more than a very small percentage of their driving. Two-stroke vehicles are not at risk, as they do not possess valve seats. Thus the impact on Bangladeshi vehicles from this change to unleaded fuel is thus likely to be quite small.

6.2 Options for Further Lead Reduction

Although the average lead content of Bangladesh gasoline has been reduced significantly in the past few months, the job is only partly completed. Lead must still be removed from the premium (HOBC-96) fuel. This is important not just for its direct health benefits, but also as a necessary step before catalytic converters can be placed on automobiles to reduce other harmful emissions. Since most automobiles (especially newer ones) appear to be fueled in part or entirely with HOBC-96, this fuel must be unleaded in order for new vehicles to be equipped with catalytic converters.

In addition, the issue of how to phase out leaded fuel must be addressed. In all countries where leaded fuel has been replaced by unleaded fuel, a phase-out program is always used. The success of such phase-outs, however, has been mixed, and their costs have often been substantial. Bangladesh is well positioned to undertake a course of transition that is cost-effective and time saving.

In order to achieve an HOBC (high octane) unleaded fuel, the octane must be raised from 86-88 pre-lead RON level to its final octane level without the use of lead. If a RON of 96 is desired, then blending RON-92 unleaded, as done currently, clearly will not be sufficient to do the job. Even blending RON-96 unleaded (also available on world markets) will not suffice, although blending these fuels can still play a role.

Further, ERL's recently announced upgrade plans represent an important opportunity. ERL plans to upgrade the refinery with a new distillation column capable of doubling the production of motor gasoline. It is also considering making investments in equipment capable of producing entirely lead-free fuel. However, if it does not make such additional investments, the presence of a new, larger distillation column would allow the refinery to revert to producing fully leaded fuel (by eliminating unleaded blends). Although a transition process to unleaded fuel has begun, its completion is by no means guaranteed.

There are at least two paths available to achieving completely unleaded fuel:

1. as gasoline consumption continues to rise in the country, blending of imported high octane unleaded gasolines (and shifting to imports of higher octane), could be continued while lowering the lead requirement of HOBC fuel, until eventually imported product achieves a proportion of total gasoline supply high enough to achieve desired octane levels without the use of any lead;
2. undertake a refinery upgrade for the domestic production of completely unleaded fuel.

These two paths need not be mutually exclusive. For example, even with an upgraded refinery capable of producing twice as much gasoline as the current capacity, there will likely be a need once again for imported gasoline to supplement the total supply in just a few years, given the recent rate of demand growth in the country. Conversely, blends will continue to play a key role until a refinery upgrade is complete, which will take a minimum of three years.

As part of either or both of these two paths, at least four possible actions are available that can contribute to achieving fuels of the desired octane without using lead:

1. Building a new reformer and isomerization unit at the refinery.
2. Blending high octane unleaded product.
3. Using other high-octane additives.
4. Shifting to production of a lower octane fuel, such as one with 92 or 93 octane, rather than the current 96 octane produced.

These are discussed in turn below.

6.2.1 Reformer / Isomerization Option

As discussed in Chapter 3, a reformer increases octane at an oil refinery principally by creating isoparaffins and cyclic compounds from straight-chain hydrocarbons. These compounds have much higher temperatures of ignition than the straight-chain compounds, and thus significantly higher octane numbers. However, many of the cyclic compounds are unsaturated, or aromatic compounds (e.g. benzene, xylene, toluene) which are suspected carcinogens.

The reformer currently in operation at the Eastern Refinery increases the octane of heavy gasoline by about 25 points (from about 52 to about 87). This reformer is nearly 30 years old. Newer reformers are capable of raising octane even higher - as high as 96 or 98 RON starting from a 52 octane naphtha (Mishra, 1997). Reformers recently installed in India are capable of achieving this level of RON while holding benzene levels below 5% (Kapoor, IIP, personal communication). This is achieved through the addition of a solvent extraction unit. However, if still lower benzene levels are required, octane levels may need to be reduced somewhat.

Alkylation and isomerization can also provide octane increases without the resulting high-aromatic content in fuel produced by reformers. However, they are more expensive to build and operate than reformers on a per unit octane enhancement basis.

The Eastern Refinery has estimated the cost of a new reformer, of 4000 bbl/day capacity, to be between 20 and 25 million US dollars. Such a reformer would provide a tripling of the reforming capacity relative to the current one. It estimates the cost of an isomerization unit of 2000 to 3000 barrels per day capacity to be about 50 million dollars. These two units together are capable of producing HOBC-96 fuel without the use of lead. The cost estimates are consistent with others' estimates, as well as with the actual costs of the three reformers built recently at Indian refineries (Mishra, 1997)

In general, the cost of a transition from gasoline with moderate lead content (e.g. 0.4 g/L) to unleaded gasoline, through refinery retrofitting of this type, has been estimated to be in the range of 1.0 to 2.0 US cents per liter, including the capital and operating costs of the new equipment (Thomas, 1995).

6.2.2 Use of Unleaded Product Blends

If no refinery upgrade is constructed, then ERL will need to continually increase the amount of gasoline product it imports to keep up with rising demand. As long as the imported gasoline is unleaded, the average lead content of fuel will continue to decline. However, it will not go to zero unless one of two steps is taken: a) importing product of octane higher than 96 (probably at least 100) in order to bring the RON rating of HOBC to 96 on a weighted average basis, or b) shut down HOBC gasoline production at the refinery altogether, and simply provide all gasoline using imported unleaded 96.

In the first case, the octane of the imported fuel would need to be 100 RON or higher to balance the 86 RON pre-leaded refinery product. At 100 RON, about a 3:1 Mixture of imported blend will be needed to bring the final HOBC product up to 96 octane. At current rates of demand growth, it will take several more years before such a ratio is achieved (unless production at the refinery is cut). In the mean time blendstocks will be insufficient to bring the octane of the HOBC fuel up to the desired level.

If the refinery were to stop producing HOBC gasoline altogether (an expensive option, since capacity that can produce gasoline cheaply will sit idle), then 96 octane fuel could be imported and sold directly on the market. The cost impacts of such an option are addressed in the next chapter.

6.2.3 Use of High Octane Additives

There are a number of high-octane, non-gasoline blends that can be used for octane enhancement instead of lead. Many of these have their own drawbacks, and in recent years the list of acceptable options has been narrowed considerably. The most popular additives in many countries are the family of alcohol and ether-based high-oxygen compounds, or "oxygenates". These include methanol, ethanol, methyl-tertiary-butyl-ether (MTBE) and ethyl-tertiary-butyl-ether (ETBE). India, Thailand, the US and many other countries are using MTBE as an important component of their strategies for producing high-octane unleaded gasoline. MTBE has an octane rating of 110 RON and can be blended up to 15% with no running problems for any gasoline ICE engine.

In Bangladesh's case it is likely that MTBE would be purchased on the world market, as the volumes required probably would not justify construction of an MTBE production unit. The cost-effectiveness of such an option would therefore depend on the prices of MTBE in the international market, which have fluctuated considerably in recent years. Recent world spot market averages have ranged from about $0.15 to $0.2 per liter. This is about 1.4 to 1.8 times the production cost of gasoline (at $0.11 per liter). A gasoline/MTBE blend of 9:1 would increase RON from 86 to about 89, at a cost of between 0.5 and 1 cent per liter (10% replacement of a liter of gasoline at an incremental cost of 5 to 10 cents per liter).

6.2.4 Reducing the Octane of Premium Fuel

The option of producing a lower octane fuel is an interesting one and deserves close examination. While premium unleaded in many developed countries is 96 or higher (in the US it ranges from 95 to 97 RON), many countries do not produce a grade of fuel with an octane rating as high as 96 RON. India's only grade of unleaded fuel has a RON of 87, although there are plans to introduce a premium unleaded with 93 RON. In Thailand, unleaded regular ranges from 87 to 92 RON (Octel, 1995). According to several sources, few vehicles have a need for fuel with a RON-rating above 90-92. Those that do are mostly high-performance European cars, and they need higher octane fuels mostly when operating at high speeds.

It therefore seems unlikely that Bangladesh needs to have unleaded (or leaded) fuel with a 96 octane rating. Unleaded fuel with a RON of 92 or 93 should provide sufficient performance for virtually all cars that will be sold in the country in the foreseeable future. Further, lowering the octane number from its current level would not preclude raising it again in the future or introducing an additional "super-premium" grade if the need arises. By lowering the octane of premium fuel, the job of reaching this octane level becomes easier and less expensive.

6.3 Issues Involved in Introducing Unleaded Fuel

The transition from leaded to unleaded fuel has been a long and complicated process in many countries. Long transitions have resulted primarily from concerns regarding vehicle/fuel compatibility, time constraints on changing over refinery operations, and health concerns. In designing a strategy for Bangladesh an appropriate goal is to minimize the time and costs of transition within constraints of technical feasibility and avoiding any unnecessary health risks associated with changing fuels.

There are four principal issues that must be considered in designing a transition policy from leaded to unleaded fuels.

6.3.1 Refinery Constraints

In order to switch from use of lead to other approaches for meeting octane requirements, a significant investment in refinery capacity is necessary. This takes time and money, and countries with many refineries find it impractical to convert all refineries at once. India, for example, has more than 20 refineries. Bangladesh's proposed refinery upgrading is expected to take up to three years from contract signing to completion.

6.3.2 Vehicle Considerations

Concerns regarding the impacts of running older vehicles on unleaded fuel have been a major reason for many countries' long and expensive transitions to unleaded fuel. Detailed analyses, however, have shown that such concerns are largely unwarranted. Estimates of the vehicle-related costs and benefits presented in the Chapter 7 below suggest that vehicle concerns should not stand in the way of a rapid transition.

One other important consideration is the large number of two-stroke vehicles in Bangladesh that produce a significant amount of hydrocarbon emissions. These vehicles probably already emit a large amount of aromatic emissions (given the high aromatic content of the fuel produced by the Eastern Refinery), and could produce even more if unleaded fuel is produced with very high aromatic content.

6.3.3 Health Considerations

The use of high aromatic-content fuel, especially in vehicles without a catalytic converter, can result in high emissions of these toxins. Some countries have taken the approach that unleaded fuel should only be used in vehicles with catalytic converters, since the converters will neutralize most tailpipe emissions of benzene and other aromatic compounds. Since catalytic converters are likely to be introduced only on new vehicles (retrofitting them on older vehicles is prohibitively expensive), this reinforces the dichotomy between leaded/unleaded fuel and older/newer vehicles, and dramatically slows that rate at which unleaded fuel can be introduced. It also forever locks out two-stoke vehicles (such as autorickshaws), since these cannot utilize a catalytic converter.

However, since vehicles are not the most significant source of aromatics, and a significant quantity of vehicular aromatic emissions are not from the tailpipe, but are evaporative, it is not clear how much benefit is provided by restricting the use of high aromatic unleaded fuel to vehicles with catalytic converters anyway. This is especially the case in Bangladesh, where the high octane leaded fuel also has very high aromatic content.

Ultimately, the issue of aromatic emissions is not so much a transition issue as it is an important issue in its own right: minimizing the level of aromatics in all vehicle fuel should be a high priority, regardless of lead content. Rather than restricting high aromatic fuel to vehicles with catalytic converters, the much better solution is to go with low-aromatic unleaded fuel in the first place.

6.3.4 Distribution System Constraints

The distribution system poses perhaps the most complex issue. If a transition is desired whereby both leaded and unleaded fuels are recommended for different vehicles and are sold simultaneously for any period of time, then the refueling system must be able to accommodate both; if either leaded or unleaded fuels need to be offered in more than one grade then the fuel distribution and retailing system would have to be modified to accommodate this additional fuel, which can be very costly.

In Bangladesh, if only new vehicles with catalytic converters were allowed to be run on unleaded fuel, it would be necessary to supply the vast majority of existing vehicles the option of running on 80 or 96 RON leaded fuels in order to accommodate all types of vehicles and drivers. This would be similar to the strategy being taken in India. It involves adding storage and pumping equipment at all retail outlets that carry unleaded (the number of which will increase through time), as well as allocating some central terminal storage capacity and transport equipment to the new fuel.

A much less expensive alternative is to replace one fuel with another at more-or-less a single point in time, for example switching from three grades of leaded gasoline to two grades with one grade of unleaded. This avoids the problem of stations having to install any new equipment[16].

Of the four issues outlined above, the first three represent potential reasons for choosing to have a significant transition period for phasing in unleaded (and phasing out leaded) fuels, and the fourth point represents a major issue that argues for choosing to have one unleaded fuel along with the leaded fuels. The impact of how these issues are handled is highlighted in the following case study presented for India.

6.3.5 Case Study: India

India is currently going through a transition from leaded to unleaded gasoline, and although it is a much larger country than Bangladesh, with a considerably more complex refining and distribution system, several relevant lessons can be learned from India's experience.

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[16] Mishra, Oil Coordination Committee, Ministry of Petroleum and Natural Gas, Government of India, personal communication.

India began introducing unleaded gasoline in April 1995. India has more than 20 refineries, and a decision was made to phase in unleaded fuel over a period of at least 5 years, bringing on-line unleaded gasoline capability one refinery at a time. As of 1997, India has constructed reforming units at three of its major refineries, and has constructed two MTBE production units. It now has introduced unleaded fuel in its four largest cities (Delhi, Calcutta, Mumbai [Bombay] and Chennai [Madras]). It has a combined total of over 50 unleaded refueling stations in these cities. Currently unleaded fuel availability is being extended on the major highways radiating out of these cities. By December 1998, the Ministry of Environment and Forests, the implementing agency, plans to have unleaded fuel available in all Indian state capitals and union territories, as well as on the major highways running between the capital cities. By March 2000 the goal is to have unleaded fuel available in every station in the country. (Chandiny, Ministry of Environment, personal communication.)

According to Indian authorities, a primary reason for this long phase-in program is concern over the use of high-aromatic-content unleaded fuel in vehicles without a catalytic converter. It also provides more time for refineries to gear up production of unleaded fuel. The aromatic content of unleaded fuels coming out of the reformers is currently fairly high, including between 5 and 6 percent benzene, but as of this year a 5% limit has been placed on benzene, with a proposed reduction of this percentage to 3% by 1999. Aromatic levels in leaded fuels may also be significant, but estimates were not available.

Due in part to this concern over aromatic emissions from unleaded fuels, Indian authorities have determined that only vehicles with catalytic converters should run on this fuel. This decision has resulted in their initiation of the complex transition scenario described above, whereby unleaded fuel is introduced in locations and quantities that must closely match the growth in vehicles with catalytic converters. As of 1995, about the same time as the introduction of unleaded fuels, India began requiring all new four-wheel gasoline vehicles to be equipped with a catalytic converter. A major advertising campaign was initiated to educate the car-owning public that all cars bought as of 1995 must use unleaded gasoline, while those bought before 1995 must use leaded gasoline. Owners are informed that their cars will not run well on the wrong fuel. The government has also set the price of the two fuels to be the same (supported by subsidizing the production of unleaded fuel) to facilitate the process. No estimates of the success of this program on avoiding incorrect fueling practice are available.

Since India has only two grades of leaded gasoline (87 and 93 RON), most stations that have added unleaded 87 RON have installed a new pump and storage tank for this purpose. The cost of these installations is estimated to be between 2.75 and 3.0 lakh Rupees (US $8000 - $9000; OCC, 1997). In a country with over 10,000 stations, this means an added cost of up to 70 million dollars to provide the additional fuel. On the other hand, India plans to eventually add a second grade of unleaded fuel as it phases down leaded, so it will take advantage of the additional pumping equipment for a fairly long time. Indian authorities are to begin a phase-out of unleaded fuels by 2001, when unleaded fuels are available nation-wide and the aromatic content of the fuel is lower. By that time the majority of gasoline vehicles in the country are likely to have catalytic converters and sales of leaded gasoline will be in decline.

6.4 Lessons and Options for Bangladesh

Would it be possible for Bangladesh to avoid a long phasing period? By having already virtually eliminated lead in MS-80 gasoline, the country has, in essence, jumped into the middle of a phasing process.

Bangladesh is in the enviable position of having a single refinery to change over, which simplifies matters greatly relative to a country like India with many refineries that cannot possibly be all converted at once. It is a fairly straight-forward matter to make the necessary investments in this refinery to allow a fairly rapid transition for the whole country.

At present, the ERL is considering making major investments in the near future. The timing of these

investments appears to be very good for making them in a way that allows a complete, rapid conversion to the production of unleaded fuel.

ERL has already floated a tender for the purchase of the first of these units, a new distillation tower. They have specified a unit with 2,650,000 tons per year capacity, about 75% larger than the current 1,500,000 capacity unit. This unit will continue to produce light and heavy gasoline naphthas with approximately the same initial octane levels, so it will have little impact on the characteristics of gasoline produced in Bangladesh.

These units have not yet been ordered, and their specifications and the timing of purchase are still under consideration. Therefore, now is time for choosing a new reformer and isomerization unit capable of producing unleaded, low aromatic gasolines.

A key transition issue is how to handle the 2-3 year period while the refinery is being upgraded. The simplest solution is to continue to blend unleaded fuel and reduce the average lead content of fuels sold, WITHOUT a major public campaign claiming that the fuels are unleaded, and WITHOUT initiating the introduction of catalytic converters on new vehicles. The first would unnecessarily raise concerns regarding vehicle-fuel compatibility, and the second would trigger the need to partition the vehicle-fuel market to keep new vehicles from using leaded fuel.

An alternative approach would be to stop adding lead immediately, and purchase blends of sufficiently high octane to meet an average HOBC RON rating of at least 92. This will be somewhat expensive in the short term, as with a 1:1 ratio of imported blends and refinery produced reformate of 86 RON, the imported blend will have to have a 98 RON rating in order to achieve a 92 average. However this will allow an immediate introduction of catalytic converters on new vehicles, and it would allow the government to correctly claim that it has achieved lead-free fuel in the country.

CHAPTER 7. COSTS AND BENEFITS OF SWITCHING TO UNLEADED GASOLINE IN BANGLADESH

7.1 Health-related Benefits

Estimating the health-related benefits of reducing lead from gasoline in monetary terms is a difficult process, with few examples in the literature. The discussion and estimates presented here are based primarily on two sources: the US EPA 1985 lead cost/benefit study and a study by Schwartz (1994) outlining issues in lead-reduction benefit estimation and making benefit estimates. Schwartz was also the primary contributor in the US EPA study. While both of these studies focus on the US context, a number of adjustments have been made to adapt them to the Bangladesh context.

The analytical steps necessary to quantify and monetize the health impacts of reducing lead in gasoline are outlined in the accompanying schematic diagram (Figure 7.1). The steps fall into two categories: physical linkages between lead in gasoline and lead in the human body, and the physical and economic costs of the presence of that lead in the body.

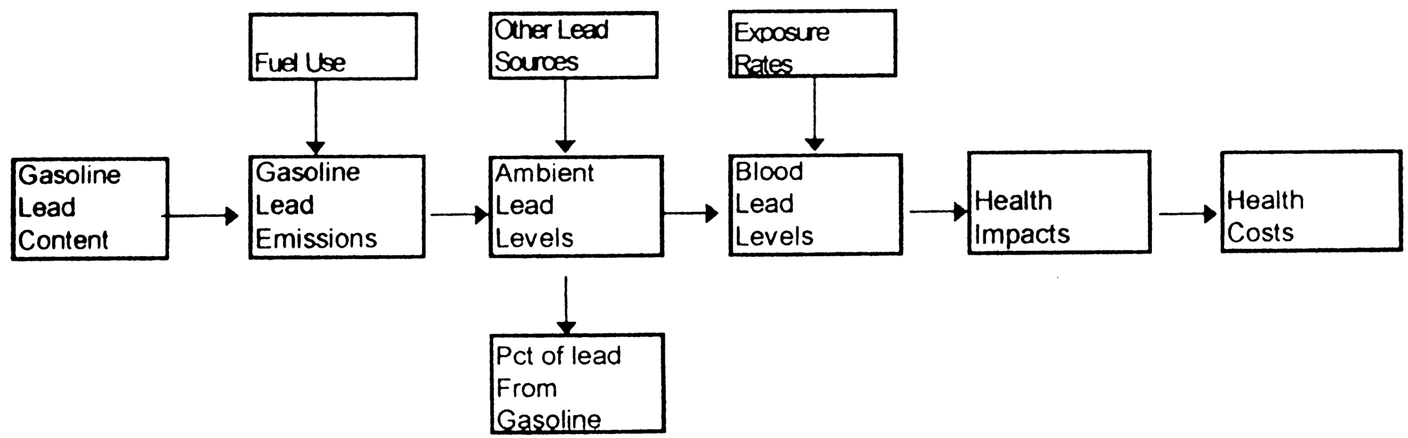
While the schematic depicts the linkages between a given level of lead in gasoline through to a given monetary cost of health impacts, it is the first difference that must be quantified: the effects of a change in gasoline lead levels through to the change in health impacts. It is therefore necessary to understand the general relationships between each linkage, and how a change at each step impacts the next step.

7.1.1 Impacts of Changes in Gasoline Lead Levels on Gasoline Lead Emissions

The percentage of lead entering the atmosphere from leaded gasoline is more or less fixed and is proportional to the lead content in the fuel. In Bangladesh the average lead content of fuel has dropped by 75% in the past 6 months, and therefore the total emissions of lead to the atmosphere per unit fuel use has also dropped by 75%. If lead is completely eliminated from gasoline, vehicular lead emissions will of course drop to zero, although traces of lead may still be emitted for several months as engine deposits of lead are "cleaned out".

Recent trends in gasoline lead content were shown in Table 6.1 in the last Chapter. In 1995-96, 89 metric tonnes (89 million grams) of lead were added to the 189 million liters of gasoline sold in Bangladesh. Assuming 80% of this lead was emitted to the atmosphere, then about 71 million grams of lead were emitted to the atmosphere. Lead use in May 97 was 2.7 million grams, a 32.4 million gram annual rate. Again assuming that 80% of this lead was emitted to the atmosphere, then if the current level of lead use continues over the next 12 months, about 26 million grams of lead will be emitted to the atmosphere. This change would represent a drop of 45 million grams of lead, or 60% compared to last year. (This reduction is less than the 75% drop in lead content per liter due to the rapidly increasing consumption of gasoline in Bangladesh.)

Figure 7.1. Linkages in Estimating the Health Costs from Lead in Gasoline



7.1.2 Impacts of Changes in Gasoline Lead Emissions on Ambient Lead Levels and Blood Lead Levels

The impact of the recent 60% reduction in gasoline lead emissions (and 100% reduction when lead is eliminated completely) on ambient lead levels and blood lead levels depends on the amount of lead entering the atmosphere, and environment in general, from other sources, as well as the amount of this lead that is absorbed by individuals.

There are also other non-vehicle sources of lead emissions. Potential non-vehicle lead sources include airborne lead emissions from factories (including power plants, smelters, brick kilns and incinerators) that use lead in production processes or combust fuels that emit lead, and non-airborne lead from house paint, water pipes, some types of pottery glazing, certain types of make-up, and disposal of lead-acid batteries.

The amount of ambient lead that is absorbed by individuals is a function of their exposure rates; i.e. blood lead levels will vary among members of the population in proportion to their relative exposure to the lead in the environment. General correlations have been developed from a number of studies comparing ambient levels with average blood lead levels. It may be possible to develop specific air lead level / blood lead level curves for Dhaka from the current testing work on blood lead levels if a larger sample is ultimately collected (by comparing blood lead content to information regarding where individuals live and work, and to ambient test data from different parts of the city). Until then it will be necessary to rely on a more generalized function.

There are several studies that have assessed both air and blood lead levels before and after removing lead from gasoline in other cities. In a new study (Fanelli 1997), over 20 localities were examined where before and after data are available. It finds that there has been a dramatic reduction in air lead levels and eventually in blood lead levels in virtually all locations. Given sufficient time for gasoline-emitted lead to be cleansed out of the air and environment (at least one year) average blood lead levels in individuals drop (on average) to 3 mg per deciliter (from anywhere from 10 up to 100 µg/dL before), with surprisingly little variation around this mean. Three micrograms per liter represents the very low end of the scale of observable impacts of lead on humans.

Similarly, a recent World Bank summary of lead phase-out experiences in different countries (Lovei, 1997) states that vehicular emissions of lead often accounts for more than 90 percent of all atmospheric emissions. Taken together, these two findings imply that atmospheric emissions are the dominant source of lead ingested by humans, and that gasoline is generally the dominant source of atmospheric emissions.

The results of the Fanelli study are especially important because they suggest that even when certain subgroups within the population are exposed to lead from non-automobile sources (such as leaded paint), the population's average exposure drop to below hazardous levels after vehicular.lead emissions were eliminated. While there is no guarantee that Dhaka will follow this norm, it is nevertheless reasonable to assume that eliminating lead in gasoline will lead to dramatic reductions in blood lead levels of exposed Bangladeshis.

In view of the very high levels of lead found in the blood samples in this study, a realistic assumption is that eliminating lead in gasoline will reduce average blood lead levels by only half (to about 25 µg).

7.1.3 Estimating the Health Impacts of Current Blood Lead Levels

In Dhaka, there are perhaps 4 to 5 million "urban core" residents. Most of those tested in this study are among the urban core. Those living in more residential areas and the suburbs may have substantially lower blood-lead levels, as tests from other cities has shown a steep gradient moving away from congested urban areas. Therefore, of the 9 million population of the city, perhaps 50 percent are relatively unaffected by high atmospheric lead levels in the urban core. This analysis will assume that 1/3 to 2/3 of Dhaka citizens are fully exposed to lead, with an average blood-lead level of 50 μg/dL, and use these figures in the estimates developed below. There are also several million living in other urban centers around the country who also probably have high blood lead levels, but in the absence of lead data for other cities this analysis will be restricted to Dhaka.

Types of Lead Exposure Effects

As shown in Table 7.1 below, there are a variety of health impacts resulting from lead exposure at or above 10 μg/dL. Some effects still occur below this level and any estimate of a lower bound "threshold" is controversial. A level of 25 μg/dL is often used in the literature as a point above which more severe effects appear to occur, and it is used by the Centers for Disease Control in the U.S. as a cutoff point for recommendation of lead reduction treatments such as chelation therapy (Schwartz, 1994).

Table 7.1. Lowest Blood Lead Levels at which Various Health Effects are Seen

Lead concentration at which the lowest observable adverse effects (μg/dL)	Health effects
100	1. Acute neurological effects: delirium, confusion and convulsions. 2. Impaired mental function.
50	Haem synthesis effects: Red blood cell survival threatened and Hemoglobin production impaired.
25-30	Peripheral nerve dysfunction, vitamin D metabolism.
10	Effects on the neuropsychological function of children, including impairment in development of IQ, hearing and growth

sources: Chapter 2, Cutajar (1997) and Fanelli (1994)

For estimation purposes, the major health impacts can be classified into four categories, two for adults and two for children:

Adults
- Damage to the nervous system
- Slight increases in blood pressure

Children
- Reductions in IQ levels and school performance
- Infant mortality due to low birthweights

Schwartz (1994), further classifies the effects of these four health impacts for estimation purposes as shown in Table 7.2. He quantifies all items in the first two columns, but does not attempt to quantify those items related to pain, suffering, and other lost utility.

Table 7.2. Health Cost Classifications

Children	Adults	Both Children and Adults
Medical Costs Compensatory Education Earnings Loss infant Mortality Neonatal Care	Medical costs due to: Hypertension Heart attacks Strokes Lost Wages due to: Hypertension Heart attacks Strokes Mortality	Pain, suffering and other lost utility from: stunted growth hearing problems increased cancers metabolic disturbances

source: Schwartz, 1994

The relationship between different blood lead levels and the specific impacts in each of these areas of course will vary across the population, and is at best shown to be statistically correlated (although accepted throughout the research community). Some of the specific health impacts of high lead levels that have been monetized in other studies include:

- The cumulative value of individuals' lost IQ to society, measured by lost productivity or wages, and the cost of increased education undertaken to compensate for lower IQs
- Additional neonatal care to compensate for low birth weights due to lead exposure
- Value of lives lost due to increased mortality
- Some aspects of morbidity, e.g. lost function from non-fatal heart attacks. However, costs of pain and suffering have not been estimated.

There are a number of difficulties in making monetary estimates in these and other areas, especially in the context of Dhaka where information is poor, and economic values tend to be very low or unknown (if services are unavailable). On the basis of two existing estimates of benefits from switching to unleaded gasoline, a new estimate is provided for one area of impact in Dhaka.

Monetized Benefit Estimates in Other Studies

Two published studies have estimated the monetary benefits of reducing human blood lead levels (EPA, 1985 and Schwartz, 1994). However, one preliminary effort has been made to estimate the costs of lead exposure in Dhaka by the World Bank (Brandon, 1997). While Brandon's estimates are quite preliminary, and for a number of reasons should not be compared directly with those of Schwartz (these reasons are discussed below), it is nonetheless interesting to view them both and consider reasons for their similarities and differences. The estimates are shown in Table 7.3 below.

Schwartz estimates costs associated with those items in the first two columns of Table 7.2. Brandon has made estimates for three items: losses from lower IQ, costs of hospital admissions and sickness requiring medical treatment, and premature deaths.

In addition to the number of items chosen to be monetized, there are at least three other very important differences in the nature of the estimates. First, one is for an entire country of 250 million people (USA) while the second is for a city of about 9 million people (Dhaka); second, estimates for the US reflect wages and medical costs commensurate with a country with an annual per capita GNP of about $25,000 while those for Dhaka reflect a situation with perhaps 1/100 this level of income. Finally, Schwartz estimates the marginal benefits from a single microgram per deciliter decrease in blood lead level (or the marginal costs of a 1 μg/dL increase), whereas Brandon's estimates are for the total costs associated with the current blood lead levels in Dhaka.

As a result, the estimates are very different in nature, and any comparisons should be made only very cautiously. Still, it is interesting to note that after accounting for both population and income differences, for similar categories Schwartz's estimates are anywhere from about equal to nearly 100 times higher than Brandon's. Since Schwartz's estimates are for the impacts of a very small change in lead exposure while Brandon's are for the total impacts of lead exposure, it seems there is a significant discrepancy between estimates of marginal and average impacts. More than anything else, the differences suggest just how difficult it is to quantify and monetize health impacts.

7.1.4 A New Estimate for One Category of Health Benefits from Blood Lead Reduction in Dhaka: IQ/Earnings Impacts

In this study, only the monetary value of blood lead reduction for a single category of health impact is estimated: IQ impacts in children as measured by changes in lifetime earnings. The method used to make this estimation follows Schwartz's methodological approach fairly closely and uses several parameters developed or cited by him. Table 7.3 below contains all assumptions and intermediate calculations.

Table 7.3. Two Sets of Estimates of the Costs of High Blood Lead Content

Source:	Schwartz, 1994	Brandon, 1997	
Estimates For:	USA in 1989 (converted to 97 dollars)	Dhaka in 1997	
Description of Estimates: (all estimates are in millions of 97 US dollars except where indicated)	Total benefit (reduced costs) from a 1µg dL reduction in blood lead level for all individuals with initial level above 25 µg/dL	Total costs to Dhaka residents of current lead levels	
		Low	High
Children:			
Medical Costs	267		
Compensatory Education	679		
Earnings Loss	7,146	8.6	33.7
infant Mortality	1,610		
Neonatal Care	95		
Subtotal	9,797		
Adults:			
Medical Costs due to:		1.5	6
Hyper tension	564		
Heart attacks	199		
Strokes	55		
Lost Wages due to:			
Hypertension	71		
Heart attacks	95		
Strokes	27		
Mortality	13,982	0.02	0.2
Subtotal	14,991		
Totals:			
US: Total Benefit per µg dL reduction	24,789		
DHAKA: Total Cost of current blood lead levels		10.12	39.9
Covered Population (millions)	250	9	9
Benefit / cost per capita (1997 US dollars)	99.2	1.1	4.4

The health benefit from switching to unleaded fuel is estimated by measuring the impacts of changes in blood lead levels on IQ in children, specifically 6-year-old children, and the impacts of changes in their IQ on expected lifetime earnings. The reason for the focus on 6 year olds is that a) this group is particularly "at-risk" to changes in IQ from lead exposure, and b) this is the most studied group in terms of establishing the relationship between lead levels and change in IQ.

It should be noted that Schwartz uses the cost of compensatory schooling as a separate category (shown in Schwartz's list of impact categories, above) which he has also quantified for the US. Since IQ scores are to a large degree a measure of learning ability, the lost learning due to lowered IQ scores can presumably be compensated to some degree with additional schooling. Such compensatory schooling is often available in the US and the benefits in terms of job prospects and wages of undertaking such schooling are measurable. However, in the Bangladesh context, where a large number of urban children receive little or no schooling to begin with, the role of compensatory education for children of lower IQ scores is likely to be extremely minor for the foreseeable future.

The relationship between blood lead levels and IQ in young children has been the subject of a number of studies. In a separate paper, Schwartz (1994b) conducted a metaanalysis that compared the results of several studies and developed a slope estimate of 0.245 IQ points per 1 µg/dL change in blood lead concentration. This estimate is based on blood lead changes between 10 and 20 µg/dL and its validity outside this range is uncertain. For this analysis two estimates are assumed: a "conservative" estimate that the elimination of lead in gasoline will result in a 25 µg/dL reduction in average blood lead content of affected citizens (from 50 to 25), and a more optimistic estimate of a 40 µg/dL reduction (from 50 to 10). Since these represent very large changes, and are largely outside the range of Schwartz's estimates, it will be assumed that the change in IQ per µg/dL change in blood lead level is only half what Schwartz found. Thus a 25 µg/dL reduction in blood lead results in about a 3 point increase in average IQ, while a 40 µg/dL change results in about a 5 point increase in IQ. This is a very conservative assumption, since the impact of changes in blood lead level on IQ could in fact be equal or even greater at higher concentrations, rather than much lower as assumed here.

The second key assumption is the manner in which lower IQ levels translate into lost expected lifetime earnings. The first step is to estimate expected lifetime earnings of the average Dhaka resident. Schwartz calculates expected lifetime earnings for six-year-olds in the US using a measure of average current earnings and a 5 % discount rate for future earnings, but also assuming a 1% real growth rate in future earnings. His estimate is adjusted here for Dhaka by taking the ratio of GNP per capita for the two countries, which is about 100:1 (25,000 v. 250 US dollars), and assuming that wages in Dhaka are about 4 times the Bangladesh average. This results in a 25:1 ratio and lifetime expected earnings for a six year old in Dhaka are estimated to be about $15,000. A major uncertainty in this estimate is the future rate of real growth in wages in Dhaka. If the country begins to experience the kind of growth that has occurred in most East Asian countries, the rate of increase in wages may be far greater than 1% annually. This would of course increase the cost associated with lost wages.

Schwartz reviews a number of studies that estimate the relationship between IQ and lifetime earnings and he divides the impacts into two categories: changes in employment rates and changes in wage rates for those employed. Taking both these effects into account, he estimates that a 1 point change in IQ will result in a 0.9% change in expected lifetime earnings. Thus a 3 point change in IQ, will cause a 2.7%, or $415 change in expected earnings for the typical 6-year old in Dhaka who is in the "affected" category. A 5 point change will result in a 4.4%, or $665 change in earnings.

Since the approach taken is to estimate the change in lifetime earnings of one age group, the resulting losses when summed over all affected members of the age group provide an estimate of the annual losses to society, as each year there will be a new group within the 6-year old cohort. If the ratio of 6-yr olds to the entire population is constant through time, then this annual figure will be reasonable; if, however, the percentage of 6 year olds within the population is growing, the estimate will understate the true costs in the future, as the group of affected individuals grows.

The final step in generating estimates for the whole society is estimating the number of affected 6 year olds in the population. The total number of six year olds is estimated to be 1/16 of those under 16, and the under 16 group is estimated to account for 40% of Dhaka's 9 million population The more important factor is the percentage of 6-year-olds that are experiencing elevated lead levels. As mentioned above, since lead emissions from automobiles shows a steep gradient as one moves away from core urban areas, those children living outside core urban areas in Dhaka may not experience significantly elevated lead levels. Most of the current testing, showing lead levels up to 75 μg/dL, has been done in the core urban areas. As mentioned, it will be assumed in making the conservative estimate that only 1/3 of all Dhaka 6-year-olds experience elevated lead levels (with a group average of 25 μg/dL), while in the high benefit case, a 2/3 assumption is used.

The resulting benefit estimates are shown in Table 7.4 below. In the low benefit case the annual benefit in Dhaka is estimated to be $31 million, while in the high case this figure is nearly $100 million. The large difference is due to the virtual doubling of two key parameters in the two cases: blood lead level reduction and the percentage of individuals with high blood lead levels.

Even the low estimate of $31 million annual benefit in IQ improvement is about five to ten times the estimated cost of switching to unleaded gasoline (the high cost case is currently 1.22 cents per liter @ 300 million liters in the year 2000 = slightly less than 4 million dollars; the low cost case represents less than 2 million dollars). Further, this is only one of about 15 different categories of heath benefits associated with reducing blood lead levels, and although it is an important category, it represents at best about 1/3 of the total benefits estimated by Schwartz. Therefore, it would appear this estimate single-handedly supports a rapid shift to entirely unleaded fuel.

Table 7.4. Estimated Benefit of Unleaded Gasoline on Expected Lifetime Earnings of Children in Dhaka (through change in learning ability as measured by IQ score)

	Category	Low Benefit	High Benefit	Notes
a.	US discounted lifetime Earnings (1997 $US)	$378,000	$378,000	from Schwartz, 1994 (300k in 89 dollars, multiplied by GDP deflator of 1.26 to get 97 dollars)
b.	Dhaka fraction of US earnings	0.04	0.04	US GNP = 25k/cap, Bangladesh = 250/cap, Dhaka = 4X Bangladesh avg.
c.	Dhaka discounted lifetime earnings (1997 $US)	$15,120	$15,120	a. * b.
d.	Change in IQ points per μg/dL change in blood lead levels	0.123	0.123	1/2 of estimate by Schwartz (1994) due to use of his estimate over much wider range of blood lead levels
e.	Percentage change in earnings per IQ point	0.90%	0.90%	Schwartz, 1994
f.	Average change in blood lead levels to "at risk" group from removing lead in gasoline (μg/dL)	25	40	assumption (see text)
g.	Total change in IQ points	3.1	4.9	d. * f.
h.	Percent change in expected earnings	2.7%	4.4%	e. * g.
i.	Total change in expected Dhaka lifetime earnings (97 $US)	$415	$665	c. * h.
j.	Number of Dhaka residents (000)	9,000	9,000	recent estimate

k.	% under 16	40.0%	40.0%	recent estimate
l.	% under 16 that are 6 yrs.	6.3%	6.3%	assumes 1/16 of under 16 population are 6 yrs.
m.	Total number of 6 year olds in Dhaka	225,000	225,000	j. * k. * l. * 1000
n.	% of 6 year olds that are fully exposed to high lead levels	0.33	0.66	assumes 1/3 to 2/3 or the population has lead levels > 10 µg/dL with an average of 25 µg/dL
o.	Total number of 6 yr old children affected each year	74,250	148,500	m. * n.
p.	**Increased Earnings from eliminating lead in gasoline** (millions of 97 $US)	**30.8**	**98.8**	i. * o. / 1,000,000
q.	**Increased Earnings per liter of fuel used** (US cents)	**16.3**	**52.3**	based on 1995-96 level of 189 million liters of gasoline

7.2 Eastern Refinery Situation Recap

As discussed above, the Eastern Refinery is currently equipped with a primary distillation column of 34,000 bbl/day capacity, and can produce perhaps 125,000 metric tons per year of naphtha (basis for gasoline). The actual gasoline output of the refinery currently accounts for only about 65% of the country's gasoline demand: imported gasoline is blended to make up the difference. Because the refinery recently switched to importing unleaded blends instead of leaded, the lead content of both fuels has declined rapidly in the past few months and will continue to decline as long as the share provided by imported fuels continues to rise.

It appears that ERL intends to expand the capacity of the Eastern Refinery regardless of any decision regarding leaded v. unleaded gasoline. This is considered necessary to keep up with the growing demand for petroleum products in the country. The plan currently under consideration is to build a new distillation column with about twice the capacity of the current one (65,000 bbl/day to replace 34,000 bbl/day). Assuming the same ratio of naphtha production with the new column, the upgraded refinery should be capable of producing 240,000 mtons per year. Based on ERL's estimates, completely unleaded final product can be produced from this naphtha by constructing a new reformer of about 4000 bbl/day (160,000 mtons/year) capacity and an isomerization unit of perhaps 2500 bbl/day (100,000 mtons/year) capacity. This will provide nearly double the current production of gasoline. The estimated cost of the reformer is 20 to 25 million dollars and the isomerization unit 40 to 50 million dollars. Although these units will allow production of completely unleaded fuel, the reformer cost should not be completely attributed to unleaded fuel production, since it would replace an existing reformer and serve as a necessary part of the capacity expansion program whether or not unleaded fuel is produced. However, a larger and more complex reformer will be needed (along with the isomerization unit) in order to produce completely unleaded gasoline.

7.2.1 Options for future production of gasoline

Given the plans for construction of an upgraded refinery, the simplest cost comparison is that between returning to production of leaded gasoline, i.e. equipping the refinery with units designed to produce only leaded fuels, versus equipping it with units capable of producing completely lead free fuel. Other options certainly exist, such as equipping it with the capability to produce one grade of leaded fuel and one grade of unleaded fuel. However analysis of more complex options is best done using a detailed refining simulation model: such an analysis is beyond the scope of this study. Further, these two options are the most likely to be undertaken and are "bounding" cases: intermediate options are likely to be intermediate in cost.

In addition to these two options for retrofitting the refinery, a third option exists for planners. The refinery could be left to continue on its current path of blending unleaded fuel and meeting future increases in demand by simply increasing the use of blends, without investing in a refinery upgrade for this purpose. If this option were pursued, high octane unleaded fuel (HOBC) could be provided by blending a higher octane unleaded fuel (perhaps 96 RON). This would also probably require a reduction in the octane rating of the final product to 92 or 93, since the closer the final fuel is to 96 octane, the more unleaded 96 octane blendstock would be needed to mix with the refinery's own 86 octane reformate in order to achieve the desired octane level. This option is also available in the interim period if a refinery upgrade is undertaken, before this upgrade is operational (which could be three years from commencement of such a project).

Therefore there are three scenarios to consider:

1. Refinery upgrade to return to the old system of producing 80 and 96 octane *leaded* gasoline in about twice the annual quantities currently produced at the refinery.

2. Refinery upgrade to produce 80 and 96 octane completely *unleaded* fuels in about twice the annual

quantities of all gasoline currently produced at the refinery.

3. Instead of a refinery upgrade (or while waiting for one), increased blending of imported unleaded gasoline with a switch to blending imported 96 octane instead of 92 octane, and a simultaneous reduction in the final octane level of Bangladesh's HOBC gasoline from 96 to 92 octane. This will allow a very rapid transition to completely unleaded HOBC fuel, and therefore all gasoline, in the country.

7.2.2 Assumptions in comparing refinery upgrade options

If the refinery is upgraded in a manner so as to produce only leaded gasoline, it is assumed that there is a return to using the ratios of fuel reforming and lead addition per ton of output that was used in 1995-96 (before imported blends became an important component of supply), but with a near doubling of total capacity. This would require a reformer with about 80,000 tons per year of capacity, roughly twice the capacity of the current one.

However, if the all-unleaded fuel refinery upgrade option is pursued, this will require construction of a reformer with about twice the capacity than for the leaded fuel option (160 v. 80 million mtons per year). Thus for the larger reformer about half of the cost can be considered incremental over the cost of a smaller reformer for leaded-only fuels. One hundred percent of the cost of the isomerization unit should be allocated to producing unleaded fuels, since this unit would not be necessary in an upgrade to produce only leaded fuels.

The resulting assumptions for the cost of building and operating a reformer and isomerization unit for a low cost and high cost case are shown in Table 7.5. For both cases, a 7% real rate of interest is assumed for the cost of capital, amortized over 10 years. Capital costs of between $20 million and $25 million for the reformer and between $40 million and $50 million for the isomerization unit are assumed. Operating costs of between $6 and $8 per ton are assumed for each unit. The cost of lead is assumed to be between $7500 and $10,000 per ton of compound (not shown in the table). These ranges reflect recent prices and estimates provided by a variety of sources.

Table 7.5 Refinery Upgrade Cost Assumptions

	Unit Capacity		Capital Costs Million $US (1997)		Operating Costs		
	Bbls/day	MT/year	Total	Annual	Dollars Per Ton	Dollars per Bbl	cents per liter
1. Low Estimates							
Reformer	4000	138.814	$20	2.59	$6	$0.67	0.42
Isomerization	2500	86.759	$40	5.18	$6	$0.67	0.42
2. High Estimates							
Reformer	4000	138.814	$25	3.89	$8	$0.89	0.56
Isomerization	2500	86.759	$50	7.77	$8	$0.89	0.56

The volumetric capacities and lead requirements to produce final gasoline products of the required octanes [MS-80 and HOBC-96]) for an upgraded refinery are shown below, for a case where only leaded fuel is produced and a case where only unleaded fuel is produced. It is assumed that 75 percent of production will be MS-80 and 25% will be HOBC fuel. Given the fact that there has been more rapid growth in HOBC fuel demand than MS fuel in recent years, these ratios will change in the future, and eventually HOBC may become the dominant fuel. However, in the near term these ratios appear reasonable.

Table 7.6. Volumetric Capacities and Lead Use Resulting from Refinery Upgrade

Scenario	Production of Intermediate Products			Addition of Lead	Typical resulting production of gasoline @75% MS-80, 25% HOBC			
					Metric tons/yr		Liters/yr (thous.)	
	Naphtha	Reformate	Isomer.	Mtons/yr	MS-80	HOBC	MS-80	HOBC
Current (1995-96)	125,000	40,000	0	228	93,750	31,250	133,313	44,438
Base Case	240,000	80,000	0	456	180,000	60,000	255,960	85,320
Unleaded Fuel Case	240,000	160,000	100,000	0	180,000	60,000	255,960	85,320

7.2.3 Resulting refinery cost estimates for producing unleaded gasoline

The resulting relative costs of producing leaded versus unleaded gasoline in an upgraded refinery are shown in Table 7.7. The avoided cost of lead in the unleaded scenarios offsets much of the cost (about half in the high cost case and nearly 75% in the low cost case) of building and operating the reforming and isomerization equipment. Taking this savings into account, the total (incremental) annual cost per liter for producing unleaded fuel is about 1 cent per liter in the low cost case and close to 2.5 cents per liter in the high cost case (Table 7.6). These cost estimates assume that both leaded and unleaded fuels are 96 RON; cost savings would accrue to both leaded and unleaded fuel production if the RON requirement were dropped to a lower number such as 92.

Table 7.7. Relative Annual Costs of Gasoline Production (under two refinery upgrade scenarios and two cases. Million US dollars [1997] except where indicated)

Case / Scenario	Reformate allocated cap cost	Reformate Operations Cost	Isomerization allocated cap cost	Isomerization operations cost	Lead Cost	Total Annual Cost	Cost per unit Dollars per ton	Cost per unit Cents per liter
Low Cost Case								
Leaded-only Scenario	1.30	0.48	0.00	0.00	4.56	6.34	$26.40	1.86
Unleaded-only Scen.	2.59	0.96	5.18	0.60	0.00	9.33	$38.88	2.73
IC of Unleaded Scen.	1.30	0.48	5.18	0.60	-4.56	3.00	$12.48	0.88
IC (cents / liter)	0.38	0.14	1.52	0.18	-1.34	N/A	N/A	**0.88**
High Cost Case								
Leaded-only Scenario	1.94	0.64	0.00	0.00	3.42	6.00	$25.01	1.76
Unleaded-only Scen.	3.89	1.28	6.48	0.80	0.00	12.44	$51.83	3.65
IC of Unleaded Scen.	1.94	0.64	6.48	0.80	-3.42	6.44	$26.82	1.89
IC (cents / liter)	0.57	0.19	1.90	0.23	-1.00	N/A	N/A	**1.89**

Note: IC = incremental cost

7.2.4 Using Imported Blends to Achieve Completely Unleaded Gasoline

Estimating the cost of using unleaded blends to eliminate lead, is in certain respects more complex and uncertain. One part is simple: since MS-80 is already unleaded, this would not change and can be excluded from the calculation. It is worth noting that the Eastern Refinery reports the current incremental cost of producing 80 octane unleaded over leaded to be zero (or negative) because the cost of blending 92 octane unleaded fuel is offset by lead savings.

However, estimating the incremental cost for HOBC-96 fuel is more difficult. This is because the current approach for producing HOBC, blending about 2 parts 86 RON reformate with 1 part 92 RON imported unleaded gasoline, and then adding lead to get to 96 RON, would change dramatically under an unleaded fuel scenario. First, it would be very expensive to get to 96 RON with blends and no lead, so a switch to production of HOBC-92 would be warranted. To get to 92 RON an approach that blends 2 parts 96 RON imported unleaded gasoline with 86 RON reformate (and no lead) would be a likely candidate. This would require a switch from a 92 to a 96 octane unleaded blend, at an incremental cost of about $5 - $6 per bbl. Further, more blendstock would be needed than before, at least in the near term, due to the much higher ratio of blends needed to reach the octane target (or, an even higher octane, and more expensive, blend could be used, such as 100 RON). On the other hand, under the current approach there is still a lead cost per barrel of product of about $1.50 to $2.00 (depending on the price of lead), and this would be saved as a result of switching.

Given current growth rates in demand, the ratio of blendstock to refinery-produced 86 RON reformate in HOBC fuel in about two years' time will be about 2:1, regardless of whether a switch to unleaded HOBC is made. This greatly simplifies the comparison. With similar blending ratios, the incremental cost of switching from 92 RON to a 96 RON blend and cutting out lead will be the difference in the cost of the two blends ($5 - $6 per barrel blend cost, or $3 - $4 per barrel of final product) minus the avoided lead cost ($1.50 to $2 per barrel). Thus the final incremental cost will be anywhere from $1 to $2.50 per barrel. This translates to about 0.6 to 1.6 cents per liter, somewhat lower than the cost estimates under a refinery upgrade scenario. However, in the very near term the cost will be considerably higher (and the analysis more difficult) due to the need to cut refinery production of reformate and replace this with the higher cost 96 RON blend in order to meet the 2:1 ratio requirement, or use sufficiently high RON imported blend to meet the octane goal with a smaller percentage blend. In either case the incremental cost would likely be somewhat more than 2 cents per liter in the short term, and could perhaps be as high as 3 or 4 cents per liter.

Although the blending approach might be fairly expensive in the short term, it would allow a very rapid transition to completely unleaded fuel. Consequently, its associated benefits would also be realized much sooner. These benefits are estimated below.

7.2.5 Transition Costs

Many countries have experienced significant transition costs when phasing out lead. They can be avoided in the Bangladesh context. The most significant reason for most countries (such as India) to undertake a long and expensive transition, as mentioned, is the desire to keep certain kinds of cars from using the "wrong" fuel, and therefore creating two gasoline fuel systems for two kinds of vehicles - leaded fuel for older cars and unleaded for newer cars with catalytic converters. As argued above, there is no longer a compelling reason for not running older cars on unleaded fuel, and such a transition is not needed. If it were to occur, however, what would its costs be?

If the Bangladesh Petroleum Corporation decided to introduce a third fuel, such as a "premium unleaded" to coexist with the premium leaded fuel for a few years, this would represent a new type of fuel that would need to have its own distribution and retailing infrastructure in order to reach consumers, at least until premium leaded fuel were phased out. The cost of this third system would be one new pump and storage tank at each station, and possibly the construction of a significant number of new storage facilities and delivery trucks. New station pumps in the US can cost over 10,000 dollars, and new in-ground tanks over 50,000. The costs in the developing world are much lower and the average cost in India has been on the order of $10,000 for both. If pumps and storage tanks were added to 100 stations in Dhaka and around the country (probably the minimum number to support vehicles that require the fuel) this would cost 1 million dollars. Other distribution infrastructure costs, such as bulk storage, extra delivery costs, and required refinery modifications will likely add an additional $1 million. For a transition lasting two or three years, it

will be very difficult for companies to amortize (recover) these costs. These investments can probably be justified only if there is a second transition, to 3 grades of unleaded fuel, when leaded fuel is later phased out. This will allow all of the new equipment to continue being used and useful.

7.3 Vehicle-Related Costs and Benefits

There are several potential vehicle-related costs and benefits from switching to unleaded gasoline. The one cost and the two most important benefits are estimated here:

- the costs of higher wear on the valve seats of some (very few) older vehicles after switching to unleaded fuel,
- the benefits from reduced wear to spark plugs and fuel oil from unleaded fuel, and
- the benefit from better fuel efficiency running on unleaded fuel.

The estimates for these impacts are all based primarily on analysis contained in the 1985 US EPA lead cost-benefit study, but are adjusted to reflect current vehicle repair costs and fuel prices in Bangladesh.

7.3.1 Costs of Valve-seat recession

Lead acts as a lubricant on piston valve seats and older, non-hardened valve seats may deteriorate quickly without this lubricant. However, most vehicles built since 1970, and virtually all since 1980 have hardened valve seats, which prevent this problem. Further, even those vehicles without hardened valve seats experience problems on unleaded fuel only when the vehicle is operated regularly at high speeds - perhaps 100 km/hr and up.

There are very few pre-1980 vehicles in Bangladesh that are driven at speeds above 100km/hr. Accordingly, the percentage of affected vehicles is estimated to be less than 1% in the high cost case, and less than 0.1% in the low cost case as shown in Table 7.8. The cost to vehicles in the U.S. with affected valves seats was estimated by EPA to be 1 cent per kilometer; the estimates have been lowered for Bangladesh due to the lower costs of auto repair in this country. The resulting estimates are one one-hundredth of a cent per liter in the high case, and one one-thousandth of a cent per liter in the low cost case. These numbers are negligible compared to other costs and benefits in the analysis.

Table 7.8. Estimated Costs of Increased Valve-seat Wear in Pre-1980 Automobiles from Unleaded Fuel Use in Bangladesh

Item	High Cost Case	Low Cost Case	Notes and Assumptions
Percent of gasoline vehicles that are four stroke	60.0%	60.0%	based on BRTA data
Percent of gasoline vehicles on-road built before 1980	20.0%	10.0%	observation
Percent of pre-1980 vehicles that have NOT had engine overhauls	50.0%	25.0%	assumes new valve seats are of hardened steel
Percent of pre-1980 vehicles operated at high speeds	10.0%	5.0%	assumes that most older vehicles do not drive on the highway and that those that do rarely achieve speeds over 100 km/hr
Percent of total vehicles with affected valve-seats	0.60%	0.08%	calculation
Cost per kilometer for affected vehicles (US cents)	0.5000	0.3333	assumes 1/3 to 1/2 of US EPA US estimate for US
Cost per kilometer for all vehicles (US cents)	0.0030	0.0003	calculation
Average cost per liter of fuel (US cents)	**0.0114**	**0.0009**	calculation (assumes similar fuel consumption per vehicle by affected and non-affected vehicles)

7.3.2 Engine Maintenance Benefits

The engine maintenance benefit from using unleaded fuel was estimated to be $17.00 per vehicle per year in the US in 1985 (US EPA, 1985). As shown in Table 7.9, this estimate has been adjusted for inflation, and then adjusted downward by 1/3 to 1/2 (in the two cases) to reflect the lower vehicle labor costs in Bangladesh. The savings to 2-wheel and 3-wheel vehicles is assumed to be only half that for cars and gasoline trucks and buses, since these vehicles have fewer cylinders and generally lower repair costs. Multiplying the per-vehicle savings by the number of vehicles of each type provides an estimate of the total annual savings for the country. Dividing this by the total annual fuel consumption results in estimates of per-liter savings of 1.2 to 1.6 cents (US, 1997).

Table 7.9. Cost Savings from use of Unleaded Fuel Due to Reduced Engine Wear to Spark Plugs and Reduced Need for Oil Changes

Item	Low Benefit Case	High Benefit Case	Notes and Assumptions
EPA Estimated savings per vehicle per year, 1985 US dollars	$17.00	$17.00	Source: EPA, 1985
Per vehicle savings per year, 1997 US dollars	$24.45	$24.45	US GDP deflator
Savings per vehicle per year for 4-wheel gasoline vehicles, adjusted for Bangladesh	$12.22	$16.28	assume savings is 1/3 to 1/2 less than US taking into account much lower labor costs and equal to somewhat higher pats costs
Savings per vehicle per year for 2- and 3-wheel gasoline vehicles adjusted for Bangladesh	$6.11	$8.14	assume savings is 1/2 less for two-stroke engines than 4 stroke, due to fewer cylinders, lower oil change and repair costs
Total number of Gasoline 4-wheel vehicles in Bangladesh, 1996	110,000	110,000	based on Chapter 4, Table 4.3 (data from BRTA)
Total number of gasoline 2 and 3-wheel vehicles, 1996	150,000	150,000	based on Chapter 4, Table 4.3 excludes 1/2 of BRTA estimated motorcycles due to uncertainties regarding this estimate
Total vehicle savings (mil 1997 $ US)	$2.26	$3.01	Calculation
Total Gasoline Consumption in Bangladesh (mil liters, 1995-96)	189	189	from Table 6.1
Savings per liter, US cents	1.20	1.59	Calculation

7.3.3 Fuel Economy Benefits

The US EPA study reviewed a large number of studies and found a range of estimates of fuel economy improvements for vehicles running on unleaded fuel of up to 5%. Here a 2% average improvement is assumed in the low benefit case and 4% in the high benefit case. Cost savings associated with this efficiency improvement is based on the pre-tax price of gasoline, since the tax-related costs represent transfer payments rather than resource costs. A price of $0.25 per liter is assumed. The resulting cost savings per liter ranges from one-half to one cent per liter. These savings would increase in the future if the world oil price rises in real terms.

Table 7.10. Cost Savings from Improved Fuel Economy Using Unleaded Gasoline

Item	Low Benefit Case	High Benefit Case	Notes and Assumptions
Percent reduction in Fuel Use	2.0%	4.0%	based on EPA survey of studies (actually estimates up to 5%)
Fuel Cost per Liter (ex taxes)	$0.25	$0.25	estimated retail fuel price in 2000 (but 1997 $) in Bangladesh without taxes (to exclude transfer cost) (about 11 Taka)
Savings per liter, US cents	**0.50**	**1.00**	calculation

7.4 Results: Total Costs and Benefits of Removing Lead from Gasoline

Results have been tabulated for annual benefits (costs) per liter for each category and overall (net benefits per liter), and have been multiplied by gasoline consumption for 1996-1997 (and estimated consumption for 2000) in order to obtain an estimate of the total net benefit to the country in those years. Year 2000 estimates are provided since this would be the earliest the refinery upgrade could be completed.

Cost and benefit estimates in each category and overall are shown in Table 7.11 for the low and high benefit cases. The low benefit estimates have been paired with the high cost estimates, and vice versa, in order to obtain estimates that reasonably bound the likely net costs or benefits.

The net benefits from those categories that have been estimated appear to be substantial. Vehicle-related benefits alone nearly equal the refining costs of switching to unleaded fuel in the low benefit case (net costs of 0.19 cents per liter) and are significantly higher in the high benefit case (1.72 cents per liter). Adding in the expected benefits in lifetime earnings from improved IQ scores in children, the net benefits per liter jump to 12.90 and 54.11 cents in the low and high cases respectively. Thus the estimated benefits of eliminating lead from gasoline exceed the costs by a factor of anywhere from 5 to 50, depending on the specific assumptions.

The total net benefit to Bangladesh from the estimated categories is between 30 and 102 million US dollars if lead were eliminated in 1997. By 2000, the savings would be between 49 and 165 million US dollars due to the expected higher consumption of gasoline at that time.

Table 7.11. Summary of Estimates of Costs and Benefits of Switching to Unleaded Gasoline (all units in 1997 U.S. cents per liter, except where noted. Costs are in parentheses)

Category	Low Benefit Case	High Benefit Case
1. COSTS PER LITER		
1A. Refining costs	**(1.89)**	**(0.88)**
Reformer Unit	(0.76)	(0.52)
Isomer Unit	(2.13)	(1.69)
Lead elimination savings	1.00	1.34
1B. Vehicle-related costs	**(0.01)**	**(0.00)**
Increased Valve-Seat Wear	(0.01)	(0.00)
Total Cost per Liter	**(1.90)**	**(0.88)**
2. BENEFITS PER LITER		
2A. Vehicle-related benefits	**1.70**	**2.59**
Reduced Engine Wear	1.20	1.59
Increased Fuel Efficiency	0.50	1.00
2B. Lead / health - related benefits	**16.30**	**52.30**
Lifetime Earnings Increase for Children	16.30	52.30
Other health benefit categories	not estimated	
2C. Non-lead Air Quality Benefits	not estimated	
Total Benefits per Liter	**18.00**	**54.89**
3. TOTALS		
Net Benefits (Costs), cents per Liter		
Excluding Health Benefits	(0.19)	1.72
Including Health Benefits	16.11	54.02
Fuel Use per year, 1995-96 (mil. L)	189.0	189.0
Estimated Fuel Use Per year, 2000 @ 10% growth	304.4	304.4
Total Net Benefits (Costs), mil US $		
Net Benefits in 1997	30.4	102.2
Projected Net Benefits in 2000	30.2	104.0

CHAPTER 8. SUMMARY, CONCLUSIONS AND POLICY RECOMMENDATIONS

8.1 Summary and Conclusions

This report has provided a detailed background of the health, technical, and economic issues associated with lead use in gasoline. It has provided the result of new tests of blood lead levels in Dhaka. Policy options available for reducing or eliminating lead in gasoline in Bangladesh are discussed and compared. Finally, estimates of all of the costs and some of the benefits of eliminating lead in gasoline in Bangladesh have also been calculated.

Three principal conclusions of this study are:

- Lead is a serious poison and has been emitted in large quantities by motor vehicles in Bangladesh. High octane gasoline still contains a substantial amount of lead. Air lead levels and blood lead levels are very high in Dhaka, although additional blood testing work is warranted to more fully characterize the distribution of blood lead levels across the population. Using extremely conservative assumptions, the annual social costs to Bangladesh as a result of damage done to the health of its urban populations (restricted to children only in the analysis) is estimated to be in the range of US$30 to 100 million.

- Lead provides inexpensive octane enhancement which is a benefit to vehicles and vehicle owners; however, there are also significant vehicle costs related to the use of lead in gasoline. This analysis estimates that benefits to vehicles of eliminating lead in gasoline range from nearly equal to the refinery costs of eliminating lead to significantly higher (nearly 2 cents per liter) than refinery costs. Once the health benefits are factored in, there appear to be overwhelmingly positive net benefits from phasing lead out of gasoline.

- Bangladesh has an opportunity to switch completely to unleaded fuel without the need for a lengthy and complex transition period. Such a transition generally involves segmenting the vehicle/fuel market and restricting different vehicle types to operating on certain fuels types. Such a transition is expensive and difficult to manage, as evidenced by the current effort underway in India. In fact the benefits of avoiding a complex transition are so apparent and significant that this becomes a major message of this report - there is no compelling need for a long transition!

8.2 Policy Recommendations

Bangladesh can move rapidly toward a lead-free gasoline system in one of two ways, both of which involve changes to the way it makes HOBC fuel:

- It can restrict output of low octane heavy gasoline and blend greater quantities of imported unleaded gasoline (of up to 100 RON) in order to get to 96 RON without lead;
- It can lower the octane requirement of HOBC fuel, to perhaps 92 RON and continue to produce heavy gasoline reformate at capacity, blending this with imported 96 higher RON gasoline as needed to reach the required octane. This option is less expensive and should provide gasoline with sufficient octane for all but a very few cars on the roads of Dhaka and the country.

The refinery can of course also switch to unleaded gasoline over a slightly longer time-frame, by upgrading the Eastern Refinery to produce unleaded gasoline. Such an upgrade may take 2-3 years to complete, but once completed will be capable of producing unleaded fuel more cheaply than can be done relying on imported gasoline blends. This study has not conducted a detailed refinery analysis, but it appears that 92 RON HOBC of moderate aromatic content could be produced at an upgraded refinery for 1-2 cents more than the cost of producing leaded fuel.

Once unleaded fuel is introduced in both low and premium grades, vehicles with catalytic converters can be sold in the country. Since most automobiles are imported from Japan and other East Asian manufacturers that already produce millions of vehicles with catalytic converters, it will be relatively straight forward to begin importing vehicles with catalytic converters at no or minimum additional cost. The faster the country moves to completely unleaded gasoline, the sooner it can begin to seriously tackle other urban air pollution problems such as smog and carbon monoxide through the introduction of catalytic converters.

8.3 Additional Research Needs

There are three significant research needs that emerge from this study:

1. It seems very possible that there is one or more significant source of lead in Dhaka besides vehicular emissions. This could be lead in water pipes, lead from cosmetics, or from some other source. A detailed study of other potential lead sources is needed to determine whether a second major source of lead is present. However, this by no means diminishes the need to reduce vehicular lead as soon as possible.
2. Additional blood lead testing is necessary in order to more firmly establish the levels of lead in central Dhaka, as well as in the suburbs and in other urban centers around the country. A larger sample size will also allow analysis of demographic, socioeconomic, and geographic variables to better understand the pathways of lead exposure and identify those groups most affected and at-risk.
3. A much lower priority, but an interesting research topic would be a feasibility study of producing alcohol or ether blends for gasoline from domestically produced biomass. As mentioned in Chapter 3, it is possible to produce high-octane blends from crop wastes that also provide oil displacement, urban air quality (CO reduction), and greenhouse gas reduction benefits. A detailed analysis of this option for Bangladesh would be worthwhile.

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APPENDIX B: TECHNICAL DISCUSSION OF LEAD USE IN VEHICLES

Gasoline Engines

Gasoline engines use gasoline as fuel. Because in gasoline engines, a mixture of gasoline vapor and air is burnt inside a cylinder, they are called internal combustion engines. There are two main types of gasoline engines, reciprocating and rotary. In a reciprocating engine, which is the most common type, the piston moves up and down or back and forth. The less common kind, the rotary engines, use rotors and will not be further discussed here.

Reciprocating gasoline engines used in motor vehicles are classified on the basis of number of piston strokes per cycle, type of compression, method of ignition, method of cooling the engines, valve and cylinder arrangements, and devices employed for the supply of air and fuel.

The number of steps, the up or down motion of the piston, involved in the combustion of the fuel-air mixture in the cylinder constitutes a cycle of steps, called strokes. Thus, a four-stroke cycle engine will have four movements of the piston, two up and two down, in one cycle. Two types of internal combustion engines, based on the number of strokes per cycle, four-stroke engines and two-stroke engines, are described below.

Four-stroke Cycle Engines

In four-stroke cycle engines, in the first stroke the piston moves down the cylinder, the intake valve opens drawing in a gasoline-air mixture. The exhaust valve remains closed. This is the intake stroke. During the second stroke, called the compression stroke, with both valves closed, the piston moves upward squeezing or compressing the fuel mixture that is already in the cylinder. When the piston reaches as high as it can go, spark plug ignites the mixture. The burning of gasoline-air mixture produces a much larger volume of a mixture of new gases. This pushes the piston downward with a great vigor in what is called the power stroke when the heat energy is converted into the mechanical energy. In the final stroke, the intake valve remains closed but the exhaust valve opens, and the piston moves upward expelling the waste gases. This *fourth stroke is called the exhaust stroke. Then the cycle begins again.*

Two-stroke Cycle Engines

In Bangladesh, three wheelers and two wheelers (scooters and motor cycles) are powered by two stroke engines. Three different types of three wheeled motor vehicles, totaling approximately 60,000 in Dhaka city alone, are currently in use. These are baby taxis (also called scooters, or auto-rickshaws), tempos (kind of microbuses) and minitrucks.

The two-stroke cycle begins when the piston moves upward and squeezes the air-fuel mixture that is already in the cylinder, and at the same time it opens the inlet to draw the air-fuel mixture in the crankcase for the next cycle. This is the compression stroke, at the top of which the spark plug ignites. The pressure of the expanding gases pushes the piston downward in the power stroke. As the piston goes down, it opens both the exhaust and the intake ports. The downward movement of the piston not only performs mechanical work but also pushes the air-fuel mixture that is already in the crankcase into the cylinder by the intake port. The air-fuel mixture being 10-30% more compressed than atmospheric air, pushes the burnt gases through the exhaust port. Thus, a two-stroke cycle engine combines the exhaust and intake steps near the end of the power stroke. The fuel that a three wheeler uses is a 50:50 mixture of gasoline (80 gasoline) and motor oil (called 'mobil' in Bangladesh). Thus, in these vehicles no extra lubricating oil is necessary.

Problems of Two-stroke Engines

During the power stroke, some air-fuel mixture also escapes through the exhaust port without being able to generate power. This phenomenon of loss of fuel mixture in this way is sometimes referred to as 'mixture short circuiting'. An estimated 15% to 40% of the fuel is short-circuited in this way (Pundir, 1989) harming the environment and causing inefficient use of fuel. There is another problem associated with a two-stroke engine: not all of the burned gases is expelled out of the cylinder. The residual gas dilutes the air-fuel mixture causing imperfect flame propagation and inefficient combustion. The major disadvantage of this is misfiring at low loads and high speeds, and consequent increased hydrocarbon emission (Pundir *et al.*, 1994).

Advantages of Two-stroke Engines

On the brighter side, a two stroke engine delivers more power for the same weight and size than does a four-stroke engine. This is primarily because each cylinder in a two-stroke engine produces a power stroke for every turn of the crankshaft, while a four-stroke engine produces a power stroke in every other turn of the crankshaft in each cylinder. Thus, two-stroke engines although not able to offer high speed, they certainly give a good mileage in spite of the fuel loss by short circuiting. Two-stroke engines are simple and easy to maintain, and thus inexpensive compared to the four-stroke engines.

To Mishuk or to Baby Taxi: Bangladesh's Three Wheelers

In Bangladesh, in the absence of proper four-wheeled taxis, the baby taxis, which are run on two-stroke engines, serve a very special purpose: unlike buses which routinely run on predesignated routes, the baby taxis carry their clientele to their respective destinations in practically the same way as privately-owned transportation does. Thus, in the context of Bangladesh, an energy-efficient, inexpensive, and flexible transport system like a baby taxi is needed. One possibility is a three-wheeler that is run by a four-stroke engine perhaps of the same power capacity as that of a baby taxi. There are a few of these vehicles already running in various places in Bangladesh. They are locally called 'mishuks'. Mishuks run on four-stroke cycle engines, these are imported from Japan, produce very little visible emission, and are as energy efficient and inexpensive as the baby taxis. There is another advantage for running mishuks. Because mishuks and baby taxis are vehicles of similar size & capacity, requiring similar support services and the number of people working for each vehicle, if the government of Bangladesh decides to reduce or eliminate baby taxis from the roads of Dhaka and else where, they can phase out baby taxis as they gradually introduce mishuks without having to find jobs for any of the people involved in the baby taxi or its support business. Licensing of baby taxis can then be stopped and that for mishuk be encouraged. Another option is a good, efficient public transport system, for example, many more buses, or a circular railway for Dhaka and other big cities or some kind of electric tram service, but these are costly affairs, and they do not take their passengers exactly to the places they might want to go. Solar power-cum- battery-operated baby taxis, still in infancy, are another option. Some of these have been introduced in India. These have the obvious disadvantage of slow speed, and they cannot travel long distances at a stretch without changing the battery.

The Compression Ratio

The compression ratio is a number obtained by dividing the maximum volume of the gasoline-air mixture at the beginning of the compression stroke by the volume of the mixture at the beginning of the power stroke. The higher the compression ratio, the greater is the force with which the piston moves downward during the power stroke. Earlier automobiles could squeeze the fuel-air mixture to one-fifth its original volume, so they had a compression ratio of about five. Modern cars have engines whose compression ratios can be as high as ten, making these engines very powerful.

Knocking

Knocking is a pinging sound that can be heard when an automobile engine is pushed too hard to produce much power very rapidly. Knocking usually results when a car is made to go uphill too quickly or to draw a heavy load too rapidly or during uncontrolled accelerations. Normally the compressed gas in a cylinder ignites when the spark plugs fire, and in that case the ignition starts at the spark plugs and travels downward. When a gas is compressed its temperature rises. In high compression cars, some gasolines ignite spontaneously at one or more places by the heat developed by the high compression even before the piston has risen to the top of the compression stroke where spark plugs are designed to fire. This causes a series of small, irregular and uncontrolled explosions which travel upward and can be heard as knocking.

These little explosions can cause loss of power during the power stroke because they do not take place in concert with the power stroke. This results into an inefficient and uneconomical use of fuel, and in severe cases additionally can damage the engine. With a particular brand of gasoline, the rule of thumb is that the higher the compression ratio of an engine, the greater is the probability of knocking.

Octane Rating

There are hydrocarbons which have great tendencies toward knocking when compressed in a high compression engine. One such hydrocarbon is the straight-chain heptane. On the other hand, there are hydrocarbons which are resistant toward knocking. An example of this kind is a branched-chain hydrocarbon, 2,2,4-trimethylpentane. Originally, this compound was mistakenly called iso-octane or simply octane because it contains eight carbon atoms in one molecule (octa means eight). The resistance to knocking is measured by a scale called the octane rating scale. In this scale, heptane which has very little resistance to knocking is given an octane value or octane number of zero, whereas iso-octane with great resistance to knocking is given an octane value of 100. The resistance to knocking is called the 'anti-knock property'. A gasoline whose antiknock properties are similar to those of a reference mixture containing 96% iso-octane and 4% heptane, under standard test conditions, is said to have an octane number of 96, and it will be called 96 octane or octane 96.

In general, straight-chain hydrocarbons have low octane value, and branched-chain hydrocarbons and aromatic hydrocarbons have relatively high octane values. This is why all the conversion processes described below aim at producing gasolines with highly branched or aromatic hydrocarbons. Table B-1 below gives the octane numbers of some representative compounds.

Table B-1. Octane values of some common hydrocarbons and compounds

Compound	Approximate octane number
Octane (straight-chain)	-20
Heptane (straight-chain)	0
Pentane (straight-chain)	60
Iso-octane (branched-chain)	100
Ethanol (commonly known as alcohol)	105
Methanol (an alcohol)	105
Methyl *tert*-butyl ether	115
Ethyl *tert*-butyl ether	118

Because octane numbers are compared in three different ways, every single gasoline has three octane numbers. These are (i) research octane number or RON, (ii) motor octane number or MON, and (iii) road octane number. The RON is determined using a special engine in the laboratory when one starts out with the gas pedal on the floor, and reflects to the conditions when a gasoline just stops to burn smoothly and knocking becomes audible during acceleration. It is the most commonly used octane number. The MON is also measured in test engines but under more realistic conditions of commercial engines, and refers more to the cruising speed along the motorway. The MON is usually 6-10 points lower than the corresponding RON. Since seasonal and climatic variations change driving conditions, neither RON nor MON are constantly useful under all weather conditions. A number which is an average of RON and MON i.e., 1/2 (RON + MON), is often used for octane rating. Thus, a gasoline with RON 96 and MON 88 will have the average value of 92 which is the road octane number. In Bangladesh octane numbers are usually expressed as RON.

In Bangladesh, two grades of gasolines are sold commercially. They are gasoline and 100 octane. The octane number of gasoline is 80 RON. This is also called motor spirit (MS 80). The octane number of 100 octane should have been 100, but as a matter of fact it is 96 RON although it is sold under the trademark '100 octane'. This is also called HOBC (high octane blending component).

Bangladesh has recently started to import reconditioned cars which are 3-5 years' old from Japan. These are cars with a high compression ratio, requiring moderately high performance gasolines. However, they should not require gasolines in excess of 93 RON to operate satisfactorily.

Gasoline

Gasoline is a highly inflammable mixture of liquids obtained from the refining of Petroleum. Petroleum is also called crude oil or simply crude. The composition of gasoline is complex, it usually contains hydrocarbons containing five to ten carbon atoms. A hydrocarbon is a compound of carbon and hydrogen only. The common hydrocarbons found in gasoline are hexane, heptane, octane, isooctane, nonane, benzene, toluene, and traces of other substances. The boiling range of gasoline used in motor vehicles varies from 27° to 221°C. In the UK, in Bangladesh and many other countries, gasoline is also called gasoline.

Petroleum Refining

The first step in the refining process of Petroleum is fractional distillation or fractionation which separates different fractions of crude oil on the basis of their boiling points. The most volatile part *i.e.*, the fraction of the crude that evaporates easily, boils out first, and is the fuel gas. The second fraction is gasoline, called natural gasoline or straight-run gasoline. Table B-2 gives a view of the kind of various hydrocarbon fractions along with their boiling ranges generally obtained from a fractionating tower.

Table B-2. Fractions of hydrocarbons obtained from distillation

Approximate boiling range, °C	Number of carbon atoms per molecule	Fraction
Below 200	4-10	Straight-run gasoline
150-275	10-14	Kerosene
175-350	12-20	Heating oil, diesel, and jet fuel
350-550	20-36	Lubricating oil, paraffin wax
Residue	Over 36	Asphalt, tar

The yield of straight-run gasoline fraction is in the range of 20%. To meet the demand of gasoline, heavier fractions are subjected to some conversion processes to change them into useable gasolines. The major conversion processes currently in use are: thermal cracking, catalytic cracking, polymerization, alkylation, isomerization, cyclization and reforming. The last three processes can be grouped under reformation, designed specifically to improve the octane rating of the gasoline.

Thermal Cracking: By this processes long-chain hydrocarbons *i.e.* heavier hydrocarbons, are broken down into short-chain or lighter hydrocarbons *e.g.*, gasoline, by the application of considerable heat and pressure. Gasoline produced by this method has a desirable property of higher octane number than does the straight distillation product (straight-run gasoline). Octane number, which is explained in detail above, is a measure of gasoline's ability to burn smoothly and efficiently.

Catalytic cracking, also called cat cracking: By this process long-chain hydrocarbons are broken down into lighter components under mild conditions of heat and pressure in the presence of a catalyst. This is a better method for producing gasoline than the thermal cracking, because gasoline with a higher octane number is obtained in a much greater yield by this process. Catalysts are substances which speed up chemical reactions without themselves actually being consumed in the reaction. Because the reactions proceed much faster in their presence, the reactions can then be carried out economically under very mild conditions.

Polymerization: Polymerization is the reverse of cracking. In this process two or more of smaller hydrocarbons (*e.g.*, methane from natural gas, propane, butane) are condensed, in the presence of a catalyst, into larger, relatively heavier hydrocarbons of high octane value. These are then employed in the making of gasoline.

Alkylation: In this process high octane fluids with branched-chain carbon skeletons are obtained by the alkylation of straight-chain hydrocarbons of low octane value. The alkylation products are called alkylates. The processes also utilizes catalysts.

Reforming processes

Isomerization: By this process straight-chain hydrocarbons of low octane numbers are converted into branched-chain hydrocarbons with enhanced octane numbers. This reforming process employs catalysts to carry out the reactions under mild conditions.

Cyclization and Aromatization: In this reformation process, open-chain hydrocarbons containing five to six carbon atoms are first converted into cycloalkanes with the loss of hydrogen atoms by a reaction called cyclization. An example of a six-membered cycloalkane is cyclohexane. When cyclohexane is further dehydrogenated in the presence of a catalyst by a process called aromatization it gives benzene which is an aromatic hydrocarbon. Toluene and xylenes, also aromatic hydrocarbons, are produced when methyl or dimethyl substituted cyclohexanes are subjected to aromatization. The products out of a reforming process are called reformats.

The Bangladesh Context

Eastern Refinery Limited (ERL), a subsidiary of the Bangladesh Petroleum Corporation (BPC) which is a semi-autonomous organization, is the only refinery in Bangladesh. It is situated at Patenga in the port city of Chittagong. The refinery is a small one consisting of a fractionating (distillation) tower, a merox unit for sweetening the gasoline by converting the hydrogen sulfides into disulfides with reduced obnoxious smell, and a small reformation unit to increase the octane rating of their premium gasoline, HOBC, by aromatization. Table B-3 displays the sale activity of ERL during the last 10 years (BPC, 1995-96). It can be seen that the sales of gasoline during the last decade have increased at the rate of respectively, 27% and 20% per year. If this growth rate reflects the rise in automobile population, then the number motor vehicles is expected to double every 4-5 years.

Currently, the demand for gasoline (80 octane) is of the order of 600 tons per day (tpd), and that of the premium gasoline (96 octane) is approximately 195 tpd. Because the refining capacity is much less than the current demand, the ERL is importing refined gasoline to blend with their products to meet the shortfall. However on a long term basis, the ERL is working on an overall plan for the increase of its facilities. Presently they are in the process of renovating their old distillation unit so that their capacity increases to 65,000 barrels per day (approx. 7263 tpd). Additionally, they have proposed to the Government of Bangladesh for approval of an expansion plan that has a provision for an isomerization unit of 2000 barrels a day capacity, a new reformer unit for aromatization of capacity 4000 barrels per day, and finally an LPG merox unit of capacity 25,000 metric tons per year. It is estimated that this four tier expansion will cost Bangladesh about US $138 million.

Leaded and Unleaded Gasolines

Octane ratings of gasolines may be enhanced by adding some organolead compounds. The common organoleads used for this purpose are tetraethyllead (TEL) and tetramethyllead

Table B-3. ERL's total sale of gasoline products during 1986-1996 (million metric tons)

Product	1986-'87	1990-'91	1994-'95	1995-'96	% increase per year
JP-1	71.3	78.5	95.3	97.1	3.6
Octane	9.5	14.8	31.2	35.3	27.1
Gasoline	58.9	92.6	156.0	174.0	19.5
Kerosene	394.0	388.0	434.0	452.0	1.5
Diesel	671.0	791.0	1275.0	1303.0	9.4
LDO	11.4	11.2	10.1	9.9	-1.3
JBO	28.3	21.5	21.5	19.5	-3.0
FO	282.0	125.0	241.0	211.0	-2.7
Lub oil	23.2	27.5	44.2	44.5	9.3
SBP + MTT	1.8	2.2	4.0	4.4	14.8
LPG	8.9	8.0	15.7	13.4	5.1
Bitumen	28.8	30.8	88.6	119.0	31.3

note: the figures for gasoline and octane show the total amount produced in the country plus that imported for blending.

(TML), although commercially three more alkylleads are available. These are dimethyldiethyl (DMDEL), methyltriethyllead (MTEL), and trimethylethyllead (TMEL) (De, 1994). The addition of less than 0.1% by volume of TEL or TML to gasoline is found to generally increase its octane rating by 10-15 points. Thus, a low-grade gasoline with an appropriate amount of added TEL or TML performs smoothly in high compression engines without knocking. These organolead compounds are called antiknock additives.

Free radicals from the thermal decomposition of hydrocarbons are formed in the cylinders of internal combustion engines where the temperatures rise up to 2200°C. These free radicals cause preignition *i.e.*, knocking, and as said above, decrease the fuel efficiency. Organolead compounds have poor thermal stability and decompose into either ethyl and methyl radicals from respectively, tetraethyllead and tetramethyllead, and atomic lead. Atomic lead then reacts with oxygen to produce oxygenated lead free radicals which participates in a chain reaction to destroy the alkyl free radicals formed from gasoline. This reduces knocking (De, 1994).

A gasoline that contains organolead antiknock additives is called a leaded gasoline. Gasolines that contain a reduced amount of organolead are called low-lead gasolines, while motor fuels which do not contain any organolead compounds are called unleaded gasolines. In theory, unleaded gasolines should not have any lead. However, the unleaded gasolines of some countries actually contain a negligible amount, up to 0.01 gram of lead per liter of gasoline, probably because of contamination during storage, transportation, use or because of geochemical reasons, but this is taken as essentially lead-free.

Problems of Lead Additives

Although organolead compounds are excellent antiknock agents, and have been used successfully as such since the 1920s, it began to be clear in the late 1950s that lead is very toxic to humans (Lewis, 1995), and to the ecosystem (WHO, 1989). It is estimated that a total of 330 000 tonnes of lead is released into the atmosphere from a host of anthropogenic sources (Nriagua and Pacyna, 1988) of which a calculated 80-90% is from automobile emission and derived from alkyllead compounds used as fuel additives (WHO, 1987). Because of the adverse health effects, from about mid-seventies many countries of the world started to set standards for lead content in their gasolines, and initiated lead reduction programs to phase out organolead additives (EEA, 1984). The USA prohibited the sale of leaded gasoline from January 1, 1996 (Octel 1995).

Another major problem associated with the use of organolead additives is that the lead compounds present in automobile exhaust, poison the catalysts of the catalytic converter (Cutajar, 1997) which makes it inefficient for the reduction of the harmful emission of carbon monoxide (CO), hydrocarbon (HC), and oxides of nitrogen (NO_x). Thus, there arose a second major health and environmental related concern for removing lead from gasoline. (For more on the converter, see below)

A third problem is the engine wear. It is known that about 75% of the added lead comes out in the emission, about 10% stays in the lubricating oil, and the rest presumably gets deposited on the inside walls of the cylinder (EEA, 1984). This lead may then damage the engine in a number of manners (as discussed above in Chapter 3).

The Valve Seat Issue

However, it is claimed that the deposited lead on the valve seats of the older model cars, protects them from being badly worn and pitted during the in and out motion of the valves. This damage to the valve seats when unleaded gasoline is used to run the vehicle would eventually allow unburned fuel to escape to the atmosphere. The damage occurs because the material employed to make the valve seats for the older cars to be run on leaded gasolines is not sufficiently hard for such wear. However, apparently this kind of damage only takes place when the car is run at high speeds for a prolonged period (Jain, 1997). In Bangladesh in the near future, there will be hardly any opportunity to drive such cars (pre 1980 models) on any motorway at high speeds for a long enough time to cause valve seat damage. The valve seats in newer model cars (most post 1980 models) are made with hardened steel that is designed to withstand this wear when unleaded gasoline is used.

Reformulated Gasolines

The adverse health effects and the poisoning of the catalysts together far outweigh the beneficial effects of valve seats when leaded gasolines are used. Thus, there arose a great need for making lead-free octane boosters additives available. The problem was circumvented by the introduction of reformatted gasolines. As mentioned above, there are several reforming processes *e.g.*, isomerization and aromatization. Isomerization produces branched-chain hydrocarbons with enhanced octane ratings, and is used in many countries as such, but the process is expensive (Ahmed, 1997). On the other hand cyclization and subsequent aromatization mainly produces benzene, toluene, xylenes which have excellent octane ratings. This last kind was introduced in many countries in the 1980s. However, benzene is carcinogenic, and toluene, xylenes and other aromatics are believed to have negative health impacts. This fact gave rise to serious concerns in the west particularly since automobile emissions from cars run on unleaded gasolines which have about 40-45% aromatics, contain substantial amounts of unburned benzene.

Catalytic Converters

The problems of automobile emissions containing unburned aromatics have been resolved with the introduction of catalytic converters. The converter is fitted in between the tailpipe and the engine. The exhaust gases, containing carbon monoxide (CO), unburned hydrocarbons (HC) including aromatic hydrocarbons, and oxides of nitrogen, can then pass through the converter containing beads of solid catalysts. The modern three-way catalytic converters have a complex mixture of catalysts, the most effective being transition metal oxides and noble metals such as palladium and platinum (Zumdahl, 1993). In the first part of the converter, a reducing atmosphere is created where oxides of nitrogen are reduced to ammonia (NH_3) and nitrogen (N_2). However since ammonia itself is a pollutant, the conditions are carefully controlled to produce a minimum amount of ammonia. In the second part of the converter, air is introduced to maintain an oxidizing atmosphere. Here CO is converted into carbon dioxide (CO_2), HC into CO_2 and water (H_2O).

In this process sulfur dioxide (SO_2) is also converted into sulfur trioxide (SO_3) which reacts with the moisture to form sulfuric acid that can cause acid rain. However, since gasoline and gasolines only contain traces of sulfur, this does not create an environmental issue of concern at the present time. In any case, the beneficial effects of the catalytic converters far outweigh this insignificant unwanted effect. It may be noted that diesel fuels contain significant amounts of sulfur, and a considerable R & D efforts are being made to produce a catalytic converter that is more suitable for diesel fuels.

Thus, in order to increase the antiknock properties of motor fuels, if aromatic compounds are used in place of tetraethyllead or tetramethyllead, it is then absolutely imperative that catalytic converters be used, unless of course one is prepared to use more expensive additives.

Octane Enhancers and Gasoline Extenders

These are materials which not only increase the octane ratings when added to gasolines, but also they are fuels on their own right. In this sense they are also called gasoline extenders. The 1970s saw the introduction of many such compounds some examples of which include *tert*-butyl alcohol (TBA), methyl *tert*-butyl ether (MTBE), and 50:50 mixture of *tert*-butyl alcohol and methyl alcohol.

Oxygenates

Another kind of gasoline extenders is the class of compounds known as the oxygenates. They are additives which when added to gasolines improve the combustion of hydrocarbons because they contain oxygen in their molecules and additionally act as fuels themselves. Thus, gasolines with oxygenate additives release less amount of unburned gasoline or carbon monoxide to the environment than those without the additives. Some common oxygenates in use are ethyl *tert*-butyl ether (ETBE), diisopropyl ether (DIPE) and ethanol.

The amended Clean Air Act of 1990 of USA puts a lower limit to how much oxygenate must be used in gasoline in order to make it environment friendly. A minimum of 2.7% oxygen by weight must come from an oxygenate additive. This means that every gallon of blended gasoline is expected to have 15% by volume of MTBE if that is the additive to be used.